LITERATURE SURVEY -
WELDABLE HIGH STRENGTH ALUMINUM ALLOYS

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Phase I - Literature Survey

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TABLE OF CONTENTS

SUMMARY

13067 over

Published information on the properties and characteristics of high strength aluminum alloys was reviewed with particular emphasis on their qualifications for use in welded cryogenic structures. The data for existing commercial alloys show that none provides the combination of high strength, notch toughness and weldability that is desired for projected booster designs. None of the readily weldable alloys develop the desired high strength, while those that are capable of meeting the strength requirements do not possess adequate weldability.

The available information concerning effects of composition, fabricating and heat treatment factors on the properties of the different types of alloys was examined to ascertain the most promising avenues for further development. The Al-Zn-Mg type alloys currently under development combine good weldability with fairly high strength and cryogenic temperature notch toughness, but further development is required to fulfill the requirements that have been established for the experimental program. The Al-Cu type alloys are also considered to offer possibilities of improvement toward the program objectives. The Al-Mg type alloys are somewhat less promising but merit some additional work. The possibility of increasing the strength of the Al-Mg_2Si alloys to the desired range is considered so remote that no development

13067

effort on them is recommended. No new alloy systems that would produce likely candidates for this program were revealed by the survey.

Recommendations are presented for the compositions and other factors to be investigated in the experimental program, and some views are recorded concerning methods of data analysis to ascertain the progress toward program objectives.

AUTHOR

INTRODUCTION

Because of their high strength to weight ratios, good retention of ductility and toughness at cryogenic temperatures, weldability and good corrosion resistance, aluminum alloys have been used extensively for fabrication of liquid fuel and oxidizer tanks and structural members of space vehicles. Non-heat treatable alloys of the Al-Mg-Mn 5000 series with yield strengths at about the 40,000 psi level have been used. Higher strengths are provided by alloy 2014-T6, with a yield strength of about 60,000 psi, and 2219-T81 at 50 - 55,000 psi in vehicles of later design.

In projecting the material requirements for the larger vehicles planned, a need for an aluminum alloy with higher strength and capable of producing higher strength welded joints is apparent. The objective of this research program is to develop a commercially producible plate alloy approaching as closely as possible the following goals: -- A tensile strength of 75,000 psi, a yield strength of 65,000 psi and an elongation of 15 per cent at room temperature and values no lower than these at -423°F (-253°C) are desired. The alloy should be as weldable as 5456 or 2219 alloys and develop joint efficiencies of 80% or more at room temperature. It should be relatively insensitive to notches, having a notched (K_t=10) to unnotched tensile ratio of 1.0 or greater at room temperature and 0.9 or greater at -423°F (-253°C). The welded alloy must remain ductile at all temperatures and have a notch tensile ratio (K_t=10) in the as-welded condition of 0.85 or greater at -423°F (-253°C). It should have high resistance to corrosion and stress corrosion cracking.

In order to ascertain the merits and limitations of alloys presently available, those currently under development but still considered experimental and alloys employed in various exploratory and survey research programs, the metallurgical publications and trade literature of the past twenty years pertaining to high strength alloys were reviewed. In addition, numerous reports based on both U.S. government contract and industry-sponsored material evaluation programs were reviewed and the findings analyzed for possible leads or approaches that might be employed in the experimental program.

This survey did not uncover any entirely new alloy systems capable of developing the high strengths required, and the most promising prospects for achieving the program objectives involve further development and refinement of existing alloy types. Thus the alloys of the groups having the Aluminum Association designations of the 2000, 5000, 6000 and 7000 series are considered individually and the possibilities are assessed of improving the desired characteristics of these alloy groups in the direction of the project goals.

6000 Series Alloys

The 6000 series alloys are of the heat treatable type, depending principally upon the controlled precipitation of the intermetallic phase magnesium silicide, Mg_2Si, for strengthening. This phase exhibits a maximum solid solubility in aluminum at the eutectic temperature, 1103°F (595°C), of 1.85% ($\sim$1.17% Mg plus 0.68% Si). The sharp decrease in solubility with decreasing temperature is the basis for the precipitation hardening of the 6000 group alloys, and those that have the most desirable combinations of strength and resistance to corrosion contain Mg and Si in the Mg_2Si proportions. Alloy 6061, for example, with nominally 1.0% Mg and 0.6% Si will form approximately 1.6% Mg_2Si. Since the solubility of Mg in aluminum is rather high and this element is an effective solid solution strengthening addition, one might presume that alloys of increased strength and lower density could be developed by increasing the Mg content of the Mg_2Si type alloys. Actually, however, exceeding the Mg_2Si ratio results in a sharp decrease in solubility of the intermetallic phase so that alloys containing an excess of Mg over the favorable ratio develop inferior strengths. On the other hand, it is well known that a small excess of Si over that needed to form Mg_2Si increases the precipitation hardening effect and thereby increases strength. It is also well known that additions of Cu to the magnesium silicide alloys increase strength. The amount of Cu generally employed in commercial alloys has been limited because resistance to corrosion decreases appreciably as this element exceeds about 0.4%. In the commercial alloys, Cr is added as a supplementary strengthener as well as for grain size control and beneficial effects on resistance to corrosion.

Among alloys of this group 6061-T6 (Table I), which has various foreign equivalents, has been used most widely for structural applications. Although the strength of this alloy falls considerably short of the objectives of this project, the alloy is notable for its relative insensitivity to stress concentrations, high tear resistance, good weldability and very high resistance to stress corrosion cracking[61-3]. This alloy with its well-known characteristics forms an appropriate base for comparison of related compositions that have been developed to provide higher strength.

Effects of Composition Factors on Mechanical Properties

A fairly comprehensive early survey of the hardening capabilities of Al-Mg-Si alloys based chiefly upon hardness measurements is that of Brenner and Kostron[39-1]. Their results disclosed the beneficial effects of excess Si over the Mg_2Si proportions and the loss in hardness associated with excess Mg. Furthermore, the improvement obtained by adding Cu up to 1% to these alloys was shown. The more recent work of Harris and Varley[54-1] presented tensile properties of sheet over a wide range of compositions which were in general agreement with the early hardness data. Figure 1, based on their data, illustrates the constant strength contours in the basic Al-Mg-Si system. For reference, the location of 6061 in this diagram is indicated. The tensile properties of 6061-T6 are higher than would be indicated by the curves because of its Cu and Cr contents. The changes in composition from 6061 required to attain higher strength are clearly indicated by this diagram, and it is apparent that two other alloys of this group, 6066, which was introduced several years ago and 6071, which is a quite recent addition to the list of commercial alloys, were designed to take advantage of these composition effects in producing higher strength.

6061-T6 Characteristics

The typical tensile and yield strengths of 6061-T6 at room temperature (T.S.-45 ksi, Y.S.-40 ksi) fall far short of the project goals. Cryogenic temperature tests of this alloy in various forms have been conducted by a number of laboratories[55-6, 57-5, 60-25, 61-9, 61-22, 61-27, 62-8, 62-11, 62-16, 62-17] and there is good agreement that the strengths of unnotched specimens increase substantially with decreasing temperature down to -423°F. Even at this temperature, however, the average values from the various tests (T.S.-79 ksi, Y.S.-55 ksi) show that the strength of this alloy is too low to be of interest in the present project. The ductility of 6061-T6 at room temperature (typical 17%) is in the desired range. Data from all laboratories are consistent in showing an increase in elongation with decreasing temperature down to -320°F and all but one show a further improvement down to -423°F. In no case was the -423°F elongation value lower than that at room temperature. The average value at -423°F is considered to be about 27%.

The aluminum-magnesium silicide alloys generally are indicated to be relatively insensitive to notches at both room and cryogenic temperatures(58-7, 60-25, 61-9, 61-22, 61-27, 62-8, 62-16). Relatively few notch tests have been made at -423°F, but the data available for 6061-T6 indicate notch tensile ratios of about 0.93 (K_t=6.3) to 0.81 or 0.75 (K_t=30) for tests of sheet specimens. With respect to notch sensitivity, unwelded 6061-T6 can be said to fulfill project requirements.

This alloy is readily weldable; however, because the heat of welding causes overaging or solution of the precipitates, depending upon the temperatures attained in different zones, the precipitate structure deterioriates and joint efficiencies as-welded are only on the order of 70%(55-2, 56-1, 56-4, 57-8, 60-1, 60-7, 60-9, 60-23, 61-3, 61-9, 61-27, 61-37, 61-38, 62-3). Improved joint efficiency can, of course, be obtained by post-weld heat treatment(55-2, 56-4, 60-9, 61-27). Other approaches to increasing weld strengths have been evaluated including the use of high Mg alloy fillers(60-14), addition of hardeners and trace elements (Cu, Mn, Na, Be) to Al-Si filler alloys(59-3, 59-5) and application of chilling during welding(62-1). Data on properties of welded 6061-T6 at -423°F are scanty but show for as-welded (4043 filler) material tensile strengths of 60-65 ksi, yield strengths of 32-34 ksi and elongations of 6-11%(60-6, 62-8). The average notch tensile ratio was 0.64.

6071 Alloy

It is apparent that although 6061-T6 exhibits many desirable characteristics, the inherent shortcoming is inadequate strength of either the parent metal or welded assemblies. Of the two newer and higher strength alloys of this group, 6071 is more distinctly of the aluminum-magnesium silicide type, is more closely related to 6061 and retains many of its desirable features. The typical tensile strength (57 ksi) is some 27% higher than that of 6061-T6 and the yield strength (52 ksi) about 30% higher. These increases in strength, achieved by increasing the magnesium silicide content, providing an excess of silicon and employing a higher solution heat treating temperature than that used for 6061, are obtained at an appreciable sacrifice in ductility, the typical elongation value for sheet dropping to about 10%. Despite its increased strength, the alloy falls considerably short of both the strength and ductility goals. This is significant with respect to the further prospects of alloys of the magnesium silicide type since even in this composition the amount of this hardener present is in excess of the high temperature solid solubility limit -- further additions would provide little or no additional strengthening.

The welding characteristics of 6071 alloy employing either TIG or MIG processes are similar to those of 6061 with either 4043 or 5556 filler[62-20]. The strengths of as-welded panels were not appreciably higher than those of welded 6061 panels. Reheat treatment and aging after welding improved the strengths, but provided no substantial advantage over 6061 similarly reheat treated. The results obtained with this alloy suggest that achievement of the strength goals through the aluminum-magnesium silicide approach would be improbable.

6066 Alloy

This alloy represents an extension of the approaches indicated previously for augmenting the strength of the magnesium silicide type alloy through a high magnesium silicide content and excess Si as well as higher Cu content than is employed in 6061. It was designed to provide tensile properties intermediate to those of 6061 and 2014 alloys. The room temperature tensile properties listed in Table I, applying to thin extrusions and sheet are very similar to those of 6071-T6. They likewise fall short of the objectives of this project by a considerable margin. For purposes of record, it may be noted that 6066 sheet has been successfully welded by the TIG process using 6066, 195 and 716 alloys as filler metal with joint efficiencies as-welded of 65-70% and 72-80% after post-weld aging[56-4]. In other tests, 6066-T6 was found to be subject to weld cracking to the extent that a welded H-plate developed cracks when either 4043 or 5556 filler was used[61-20]. Information on the notch sensitivity or tensile properties of this alloy at low temperatures was not disclosed by the literature survey. There seems to be little to recommend it as a candidate in the present project.

Other Alloys

The published literature contains reference to a number of compositions of foreign origin[references cited previously]. For the most part, these are very similar to 6061, and foreign equivalents of the higher strength U.S. alloys apparently have not been established.

Summary -- 6000 Series Alloys

The alloys of this group possess desirable characteristics of weldability and relative insensitivity to stress concentrations and cryogenic temperatures. Their modest strengths, which become even lower on welding, make the group unpromising. Furthermore, the possibility of increasing the strengths to the desired range is considered so remote that no further development effort on them in the project is recommended.

5000 Series Alloys

The 5000 series alloys have magnesium as their major alloying addition. The solid solubility of this element at the eutectic temperature, 844°F (451°C), is quite high, approximately 15%, but drops sharply with decreasing temperature to about 4% at 392°F (200°C) and is quite low at room temperature. In the case of other solute elements a decreasing solubility with decreasing temperature relationship of this type may be quite beneficial, providing a basis for substantial strengthening through precipitation. However, the effects of precipitation in Al-Mg alloys on strength are imperceptible below 9 or 10% Mg. For this reason, the 5000 series alloys are generally classed as non-heat treatable, and magnesium is employed primarily as a solid solution strengthener. When the magnesium content retained in solid solution exceeds about 3.5%, a tendency for precipitation of the excess in the form of the Al-Mg intermetallic phase exists at atmospheric and slightly elevated temperatures. This precipitation, which normally occurs preferentially at grain boundaries and increases with the degree of supersaturation of the solid solution, tends to place a limitation on the Mg content of alloys for commercial application, since its presence may promote susceptibility to stress corrosion cracking[58-2, 62-22]. It might be considered unfortunate that no means are known for increasing the low temperature solid solubility of Mg or of completely stabilizing the high Mg solid solutions at room or slightly higher temperatures. As a matter of fact, the presence of other solutes along with Mg generally tends to promote more rapid and extensive precipitation. In recent years, however, fabricating methods involving closely controlled temperatures and working practices have made it possible to produce more stable and stress corrosion resistant structures in the highest Mg content alloy now available commercially. It is considered possible that these special procedures may be applicable to alloys based on this system but more highly alloyed to achieve higher strength levels.

The commercial alloys generally contain manganese and chromium as supplementary strengtheners. These elements also serve to control grain size. The only other major alloying element occurring in the higher strength listed compositions of this group is zinc, which is employed in one experimental alloy.

As a group, these alloys are outstanding in several respects in relation to the project requirements. The weldability of the alloys having the highest magnesium contents is excellent. The resistance to corrosion and stress corrosion cracking of the commercial alloys in approved tempers is very high. Ductility as measured by elongation values at temperatures down to -423°F remains at least equal to that observed at room temperature[60-6, 61-10, 61-34]. The notch tensile strengths generally increase with decreasing temperature although the rate of increase in this value is less than that of the unnotched tensile strength so that at -423°F notch ratio values of 0.6-0.7 are observed with the highest strength alloy and temper. In this respect, some improvement is required to meet the project goal. The most significant shortcoming in relation to the goals, however, occurs with respect to the tensile and yield strengths. Based on room temperature values (Table I and Figure 2), an increase of at least 20 ksi in both is required.

Effects of Composition Factors on Mechanical Properties

In considering the prospects for increasing strengths of 5000 type alloys beyond present capabilities of commercial alloys, it is pertinent to examine available data showing the effects of variation in Mg and Mn contents. The annealed (-0) temper tensile properties of laboratory produced 0.5" thick plate of three alloy series containing 0.1, 0.5 and 0.9% Mn are plotted in relation to Mg content for a range from 2 to 7% Mg in Figure 3[58-2]. Corresponding data for the stable, hot rolled -H321 temper are shown in Figure 4. The strengths of welded joints with parent metal fillers would generally be expected to fall somewhere between values for these two tempers if the parent metal were initially in the -H321 temper. The properties of the same group of alloys cold rolled to the -H14 temper are shown in Figure 5. Because of the well-known age softening characteristic of the Al-Mg alloys, it has been customary to apply a thermal treatment after the strain hardening operation to stabilize the mechanical properties. This results in some lowering of strength, and the properties of the resulting -H34 temper for these alloys are shown in Figure 6. It may be observed that the tensile and yield strengths in all tempers increase progressively with increasing Mg content over the range shown, the change being nearly linear for -0, -H321 and -H14 tempers. The data for the -H34 temper, however, show a diminishing rate of increase with increasing Mg. The effects of Mn on strength are additive to those of Mg and are relatively linear over the 0-0.9% range. Chromium also increases the strengths in a manner similar to Mn. The content of these elements (Cr and Mn) that may be incorporated in the alloys is limited, however, by the necessity for avoiding segregation effects and the formation of coarse particles of a primary intermetallic phase.

If the linear increase in strength in the -H14 temper continued beyond 7% Mg and this temper could be produced in alloys with higher Mg content, 8.5% Mg and 0.9% Mn would be required to attain the desired room temperature tensile strength. A considerable further increase in Mg would be needed to attain the 65 ksi yield strength. The data for stable tempers, however, indicate very little probability that these strength levels could be achieved by increasing Mg content.

Cryogenic Temperature Mechanical Properties

Cryogenic temperature tensile and notched tensile data for several alloys of this series have been reported by several groups(60-6, 61-10, 61-34). Representative data are shown in Table II. In order to determine the trends in the notch behavior with increasing Mg contents, -423°F tensile and notched tensile strengths and notch tensile ratios were plotted in Figure 7 in relation to reported Mg contents of the alloys or nominal contents when analyses were not reported. It must be pointed out that all the tests are not strictly comparable since different types of specimens were used by various investigators, the notch stress concentration factors varied from 6.3 to 17, and data included different tempers although all were of -H3 type. Scatter bands drawn to encompass the data points indicate that over the range from about 2.5 to 5.25% Mg the -423°F tensile strength increases to about 4% Mg then decreases somewhat with increasing percentages of this element. The -423°F notched tensile strength tends to remain nearly constant up to 4% Mg but decreases rather sharply beyond this level. The notch tensile ratios appear to decrease progressively with increasing Mg over the range covered by these tests. These results, though influenced by other variables, indicate strongly that the -423°F notch sensitivity of these alloys increases rather sharply as the

Mg content exceeds about 4%, and if this trend continues, higher Mg alloys would be of little interest.

British and European wrought alloys containing nominally 7% Mg with an allowable upper limit of 8% have been used for many years in annealed and as-fabricated tempers. No cryogenic data for these materials were uncovered in the literature survey to permit comparison with the results obtained on the American alloys, although British data have been published for 4 and 5% Mg alloys[58-7, 58-11, 61-16, 62-10]. Recent Russian literature[48-1, 59-2, 62-22, 62-37] evidences considerable current interest in compositions of high Mg content for wrought products as well as castings. (Solution heat treated castings containing about 10% Mg have been used in the U.S. and abroad for many years.) Awareness of the stress corrosion hazard with high Mg wrought alloys under certain conditions is apparent in the Russian publications and special thermal practices as well as additions of Zn, Zr and Be are claimed to improve resistance[62-22, 62-37]. Some precipitation hardening occurs in 10% Mg alloys and is accentuated by small (0.5-1.0%) additions of Zn[37-1, 51-4, 55-3, 59-2, 62-37]. A 7% Mg alloy was included in a recent U.S. Army contract program to develop improved armor plate[61-20]. This alloy did not rate higher than 5083 in ballistic tests. Additional information on the characteristics of this material was not available.

Modifications in composition other than by increasing Mg content to achieve higher strength should be considered.

Increases in Cr or Mn are effective but are subject to limitations mentioned previously and are more detrimental to elongation than amounts of Mg which provide an equal increment of strength. This is apparent in Figures 4-6. This approach has little to recommend it. Addition of Zn offers the possibility of supplementing the strength through precipitation and improving strengths of welds and the heat-affected zone by re-aging at room temperature. Copper additions might have similar effects, although it is anticipated that the tendency for weld cracking would be greatly increased with even small additions of this element.

It might appear that increased cold work would be another approach to developing higher strengths. Unfortunately, this approach poses a number of practical problems stemming primarily from the extremely high rolling mill pressures required. The additional cold work would also accentuate age softening and tend to accelerate precipitation, increasing susceptibility to stress corrosion cracking[58-2]. Moreover, the strengths of the welds would show much less improvement than those of the parent plate.

Welding and Characteristics of Weldments

The technology of welding with the Al-Mg alloys has advanced to a high level of development. Because of the excellent welding characteristics of the higher Mg alloys of the group, they may be welded by a variety of methods and are less sensitive to process variables than many other aluminum-base alloys. There is an abundance of literature providing sources of information on welding techniques and effects of composition and process variables.

There is extensive documentation from many sources of the high joint efficiencies, good cryogenic temperature properties and relatively low notch sensitivity of welded joints attained in the commercial alloys of higher Mg content[60-6, 61-34, 62-30, 63-16]. The weld property data listed in Table II are representative of the type of data available.

Weld cracking tendency is highly dependent upon Mg content, the maximum sensitivity to this defect reportedly occurring at about 4% Mg in binary alloys of high purity[51-3, 54-3] and at a lower level, 2% Mg, when Fe and Si are present in normal impurity concentrations[50-4, 61-2]. The cracking tendency decreases with increasing Mg beyond 4% so that at 6% the alloys are virtually crack-free. Titanium is customarily added to the fillers and is considered essential to provide greatest freedom from cracking[50-4, 61-7].

Relatively little experimental work has been reported with alloys having Mg contents over 6%, but an early reference indicates that joint efficiencies generally decrease as the element increases[40-2]. This is assumed to have resulted from dendritic segregation and intergranular deposition of the relatively brittle Al-Mg intermetallic phase in the weld deposit and possibly precipitation in the heat affected zone, both of which would reduce the ductility and toughness of the joints. Possibly more modern welding methods would minimize this tendency. It has also been reported that weld unsoundness becomes more prevalent at higher Mg levels(55-4, 61-4). To counteract this effect, chlorine additions to the shielding gas might have value(55-7).

Considerable work has been done to improve Al-Mg filler alloys to increase the strength of TIG welds in 5083 plate weldments(61-20). Strength was increased by raising Mg content or adding Zn. The Zn-free Al-Mg-Mn TIG weldments were not susceptible to stress corrosion or galvanic attack, but those containing Zn were highly susceptible, the degree of susceptibility increasing with Zn content. Furthermore, multi-pass MIG welds employing Zn-containing fillers developed grain boundary networks of brittle constituents with resulting embrittlement of the welds.

Summary -- 5000 Series Alloys

Although the prospects for meeting the strength and cryogenic notch toughness requirements with alloys of higher Mg content than those presently established as commercial in this country do not appear particularly encouraging, it is considered that a section of the experimental program of modest proportions should include an exploratory evaluation of their characteristics. In particular, the use of an addition of Zn to the plate alloy as well as the filler to provide age hardening of the weld and heat-affected zones is suggested.

2000 Series Alloys

The Al-Cu system is the basis for some of the oldest and most important structural alloys in use today. This is a precipitation hardening system with a maximum solubility of 5.65% Cu at the eutectic temperature and less than 0.2% Cu at room temperature. The majority of the commercial alloys contain less than 5% Cu, although one alloy, 2219, which is outstanding among those that are available commercially because of its combination of weldability, strength and insensitivity to stress concentrations at cryogenic temperatures, contains 6.3% Cu.

2017, 2014, and 2024 Alloys

Among the oldest of the commercial high strength aluminum alloys are the so-called "Duralumins" containing 4-4.5% Cu and 0.5-1.5% Mg. In these alloys, additions of Mg have been made to increase the response to age hardening[59-4]. The strongest and most important structural alloys of the Al-Cu-Mg type include 2017, 2014, and 2024 (Table III). Alloy 2017 does not respond well to artificial aging and therefore is employed in the naturally aged -T4 temper. Alloy 2014 is employed only in the artificially aged -T6 temper, while 2024 is employed in the -T3 and -T4 tempers, the artificially aged -T6 temper, or the cold worked and artificially aged -T81 or -T86 tempers, which are limited to light gauge plate and sheet. Typical properties for these alloys are shown in Table III. The yield strength of 2017-T4 is 40,000 psi at room temperature. This compares with a yield strength of 50,000 psi for 2024-T3 and strengths of 57,000 - 60,000 psi for 2024-T6 and 2014-T6. The -T8 tempers of 2024 provide higher strengths that approach the desired goals but have low tensile elongations.

The tensile properties of 2014-T6 and several tempers of 2024 are shown in Table IV for temperatures as low as -423°F. The data are those of Christian and Watson[62-8], and are for samples with and without a sharp notch. The results of these and other tests[61-40, 62-17, 63-10] show that 2014-T6 and 2024-T3 have good notch-tensile ratios at temperatures as low as -423°F (0.8 or greater for K_t=6.3). The tensile strength and yield strength of 2014-T6 are substantially higher than those of 2024-T3 and approach the goals set for the present research project. The tensile elongation of 2014-T6 at room temperature is about 10%, however, substantially below the value of 15% established as a research objective. There are few data on the notch-toughness of the -T8 tempers of 2024[49-1]; however, available results indicate that these tempers have lower elongations at room and cryogenic temperatures than 2024-T3 or 2014-T6, and probably greater notch sensitivity.

Numerous studies of the weldability of 2014 and 2024 have been carried out. Results show that satisfactory welds and good weld strengths can be obtained with the proper selection of welding conditions and filler alloy[62-31]. The highest strengths and greatest efficiencies are obtained when reheat treatment of the weld is possible; however, considerable success has been obtained in increasing the strengths of as-welded structures through careful joint design, weld area reinforcement, and rapid chilling[63-2].

In general, alloy 2024 has not been used much in welded structures because of greater difficulty in welding and lower weld properties than are obtained with 2014-T6. The preferred filler wire for use with 2024 is 4043, although 4543 and 2024 have also been employed.

Alloy 2014 is employed currently in welded missile applications. Both weldability and weld strengths are superior to those of 2024; however, the welding characteristics of 2014 are not as good as those of the 5000 series alloys and 6061. The recommended filler alloy for 2014 is 2319, although 4043 and 2014 are also used[62-31]. Weld ductility is low and repair welding of both 2014-T6 and 2024-T3 is very difficult.

Some weld properties for 2014-T6 are shown in Table IV at room and cryogenic temperatures. Results show an increase in the strength of the joint with decreasing temperatures. There is also a decrease in tensile elongation and some increase in notch sensitivity[62-8] with decreasing temperatures.

<u>2219 Alloy</u>

The Al-Cu alloy, 2219, has welding characteristics that are greatly superior to those of the Al-Cu-Mg alloys. Alloy 2219 contains 6.3% Cu plus small amounts of Zr, V, Ti, and Mn. The excellent welding characteristics of this 2000 series alloy are due to the high Cu content, the elimination of Mg from the composition, and the grain refining effects of the elements Zr, V, and Ti. The weldability of 2219 using 2319, a parent type filler, is similar to that of 5000 series alloys[(62-31)].

The tensile properties and notch tensile strengths of 2219 in the -T6 and -T8 type tempers are shown in Table IV at room and cryogenic temperatures. Weld properties are also shown. In comparison with 2014-T6, 2219 in the -T81 and -T87 tempers has slightly lower strengths but greater notch toughness at temperatures to -423°F[(62-8)]. Weld joint efficiencies for 2219 are similar to those of 2014-T6. Welded joints, employing 2319 filler, have low notch sensitivity[(63-9)].

Other 2000 Series Alloys

Other 2000 series alloys appear to have less satisfactory properties for aerospace and cryogenic purposes than alloys 2014 and 2219. The Al-Cu-Li-Cd alloy, 2020, has higher strengths[(60-22)] than 2014, 2024, or 2219 (Table III), but is considerably more notch sensitive and has extremely poor weldability[(59-9)]. The ductility of 2020-T6 is also low by comparison with 2014-T6 and 2219-T81. Alloys 2618, 2018, and 2218 are forging alloys containing 2.3-4.0% Cu, 0.6-1.5% Mg, and 1.0-2.0% Ni. The addition of Ni is primarily for strength at elevated temperatures and contributes little to room temperature properties. As shown in Table III none of the alloys has strengths as good as those of 2014-T6. Cryogenic tests[(61-36)] have shown that 2618-T6 has good notch properties down to -423°F. It is more difficult to weld than 2014 or 2219 and has lower strengths.

Alloy 2025 is another forging alloy, containing 4.5% Cu and 0.8% Si. Similar alloys have been employed in Germany[28-1]. British experiences[55-8] indicate such alloys are weldable; however, strengths are well below those of 2014 and 2219 (Table III).

Attempts have been made to increase the aging response of Al-Cu alloys with additions of Sn, Cd, and In. An alloy of this type (27S - Table III) was introduced by Alcoa as early as 1932; however, the most comprehensive published work of this nature is that of Hardy[52-3, 55-5]. His results showed that substantial gains in strength can be obtained with as little as 0.05% of these elements in alloys containing 4.5% Cu. Unfortunately, the strengths obtained by such combinations fall short of those of 2014-T6 or the -T8 tempers of 2219. Additions of Cd or Sn cannot be used to enhance the properties of alloys such as 2014, since Mg renders these additions ineffective. There is the possibility that such additions could be used to increase the strength of alloy 2219, which does not contain Mg. Such claims have been made in Japan for an alloy containing 6% Cu, 0.3% Mn, and 0.9% Cd. Tensile properties of this alloy after artificial aging were reported to be tensile strength - 75,000 psi, yield strength - 62,000 psi, and elongation - 9%.

The resistance to corrosion and stress corrosion cracking of 2000 series alloys is dependent upon the product and the thermal treatment. The maximum resistance to corrosion attack in aluminum-copper-magnesium alloys is attained with the naturally aged condition (-T4 temper) if the rate of quenching from solution treating temperature is rapid. Slower quenching rates obtained with thick sections (plate or forgings) quenched in cold water can lead to lower stress corrosion resistance. Artificial aging improves the resistance to corrosion of slowly quenched 2014 and 2024 products, if the aging is extended somewhat beyond that required for maximum strength. The stress corrosion resistance of 2024-T6, -T81, -T86, and 2219-T81, -T87 is excellent compared with 2014-T6. Alloy 2020 also has very good resistance to stress corrosion.

Summary -- 2000 Series Alloys

In summary, 2014 and 2219 have the most attractive properties among commercial alloys of the 2000 group for applications in the aerospace field. Future research should explore the possibilities of improving the strengths of these alloys and the weldability of 2014 through modifications of the base composition and through additions of modulating elements such as Cd. It is recommended that the experimental program include exploration of the characteristics of alloys based on these indicated approaches. As a matter of comment, it may be noted that in the development of the more recently established alloys of this group, considerable emphasis was placed on their elevated temperature properties and very little, if any, attention was given to weldability or cryogenic temperature properties. It is anticipated that with improvement in these latter properties as primary objectives, research may disclose beneficial effects from some compositional or thermal treatment variations that were previously discarded as of no value at elevated temperatures.

7000 Series Alloys

Heat treatable alloys of the 7000 series contain Zn and Mg as the principal hardening elements, and may or may not contain Cu. Since the characteristics of Al-Zn-Mg alloys with and without Cu are somewhat different, they will be treated separately here.

Al-Zn-Mg Alloys

Al-Zn-Mg alloys containing more than about 3% Zn and 0.5% Mg are capable of precipitation hardening. Strengths increase with increasing solute content as shown in Figure 8, which has been adapted from the work of Cook, Chadwick, and Muir[51-1]. Optimum alloy compositions appear to be those located in the region of the phase diagram identified with the T($Al_2Mg_3Zn_3$) and M($MgZn_2$) phases[51-1, 59-10].

As shown in Figure 8, alloys with high Zn and Mg contents develop strengths of the desired order. Available information indicates that higher strengths are possible for many of these alloys, using more severe artificial aging practices. The alloys employed by Cook, Chadwick, and Muir were of commercial purity and contained small amounts of Mn and Cr. Herenguel[47-3] has reported that Mn and Cr decrease the tendency for intergranular fracture in high-strength, high-purity alloys containing more than 9% of Zn plus Mg.

One of the problems associated with the Al-Zn-Mg alloys has been their susceptibility to intergranular corrosion and stress-corrosion cracking. As shown by Hansen, Muhlenbruch, and Seeman[40-1], this is a function of composition, alloys containing less than 6% of Zn plus Mg being relatively free from stress-corrosion cracking and those with more than 6% showing considerable susceptibility. Other investigators have also reported that the high strength Al-Zn-Mg alloys have poor resistance to stress corrosion[43-1, 44-1, 57-3].

Because of stress corrosion, the commercial development of the ternary Al-Zn-Mg alloys has been very slow. Some use of heat treatable alloys of this type was made by the Germans in World War II because of the shortage of Cu; however, stress-corrosion cracking of these "Constructal" alloys limited their use severely. The composition and tensile properties of such an alloy, AlZnMg 3, are shown in Table V.

Also shown in Table V are the composition and properties of another Constructal type alloy known as Unidal, Unidur, or AlZnMg 1. This alloy is used in Europe for a variety of structural applications and has been described by Brenner[61-5] and others[58-1, 60-14] in some detail. The low Zn plus Mg content of Unidal and the addition of Cr provide good resistance to stress corrosion[63-8]; however, strengths of AlZnMg 1 are well below the desired levels. Similar alloys in the U.S.A. include X7003 and X7005. The results of tests on

X7005 (Table VII) show that this alloy has excellent notch strengths at cryogenic temperatures.

Other alloys[62-18, 63-13] of the Al-Zn-Mg type are X7006, X7038, and 7039. The compositions and properties of these alloys are shown in Table VI. There appear to be few data on the properties of X7038. Except for Cu content, however, it closely resembles the high strength aircraft alloy 7079 in composition and should therefore have strengths approaching the desired goals. Alloys X7006 and 7039 are of lower strength than X7038 and have properties similar to those of 2219. The strengths of the Al-Zn-Mg alloys increase at cryogenic temperatures, as shown by the data in Table VII. The notch toughness of X7006 and 7039 at room and cryogenic temperatures is good, although notch-tensile ratios of the strongest tempers appear to decrease more rapidly at cryogenic temperatures than do those of 2219 alloy.

Based on European experiences[40-1, 52-4, 63-7], alloys X7006, X7038, and 7039 would be expected to show some susceptibility to stress corrosion cracking. This is confirmed by tests on X7006, which indicate some susceptibility in the short transverse direction. No published data are available on the stress corrosion characteristics of 7039 or X7038; however, it would be anticipated that 7039 would show moderate susceptibility to stress-corrosion cracking and X7038 an even higher susceptibility.

The weldability of the new Al-Zn-Mg alloys is being evaluated[63-3, 63-5] and investigations of other experimental Al-Zn-Mg alloys are in progress[63-15]. Results indicate that these alloys have good weldability, although not as good as that of 5456 or 2219. In general, weldability is improved with increasing Mg contents up to about 3%[59-7] and is not much affected by small additions of Cr or Mn[61-32]. Al-Mg and Al-Mg-Zn filler alloys are recommended for MIG and TIG welding.

The Al-Zn-Mg alloys show weld efficiencies equal to or better than is obtained with 2000 series alloys, and better weld ductility. Since the Al-Zn-Mg alloys are relatively insensitive to the rate of quenching, welds in these alloys generally do not require post-weld heat treatment to develop good strengths. Natural aging of X7006 for several weeks will produce a stronger joint than can be obtained with nonheat-treatable alloys[63-13]. Artificial aging usually provides even higher strengths and joint efficiencies.

Al-Zn-Mg-Cu Alloys

The development of the commercial Al-Zn-Mg-Cu alloys has been described by Dix[50-3], with special attention to the problem of stress-corrosion cracking. Other investigators[51-1, 59-2] have also reported on various aspects of this development. Results of these investigations show that the addition of Cu to the Al-Zn-Mg alloys increases strength, improves resistance to stress corrosion slightly and reduces electrode potentials. Since the Al-Zn-Mg alloys are anodic to other structural alloys, the reduction in electrode potential tends to improve the compatibility of different alloy types and to minimize the possibility of galvanic corrosion.

The commercial Al-Zn-Mg-Cu alloys are listed in Table VI. Alloy 7075 is the best known member of this family and has been employed principally in military aircraft as sheet, plate, and structural members. Alloys 7178 and 7079 are also aircraft alloys. Alloy 7001 is a high strength extrusion alloy, and 7076 a forging alloy. Applications for the latter alloys have been quite limited. Two Al-Zn-Mg-Cu alloys of lower alloy content and lower strength are 7277 and X7002. Alloy 7277 is a rivet alloy but has been produced experimentally as sheet and plate. Alloy X7002 is a recently introduced composition for various structural applications including service in the cryogenic field.

With the exception of 7277 rivets, Al-Zn-Mg-Cu alloy products are employed in the heat treated and artificially aged tempers. Typical room temperature properties for the alloys are shown in Table VI. Because of the high strengths obtainable with alloys such as 7075, 7079, and 7178, the possibilities of using these in cryogenic service has been investigated[60-6, 61-40, 62-2]. Results of tensile tests and notched tensile tests are shown in Table VIII. It would appear that these alloys are too notch sensitive for many cryogenic applications.

The notch strengths of X7002 are also shown in Table VIII. Although this alloy has lower strengths than 7075, 7079, and 7178-T6 in the unnotched condition, notch strengths and notch-tensile ratios are significantly higher. In general, the notch toughness of X7002 would appear to be about the same as that of an Al-Zn-Mg alloy having the same level of strengths.

The weldability of the Al-Zn-Mg-Cu alloys is relatively poor in comparison with alloys such as 5456 and 2219, and inferior to the Cu-free Al-Zn-Mg alloys. Satisfactory welds can be made in alloys such as 7178 and 7075, however, with careful control of welding conditions and using 4043 or 5000 series alloy filler[62-9]. Similar results are obtainable with alloy X7002[63-5]. The weld properties of some of these alloys are shown in Table VIII.

Mention has already been made of the resistance to stress corrosion of the Al-Zn-Mg-Cu alloys. The successful exploitation of these alloys in sensitive aircraft applications can be attributed to improvements in resistance to stress corrosion achieved by composition control and the use of Cr to influence precipitation[50-3]. As a result, these alloys have good resistance to stress corrosion in all but the short transverse directions of heavy sections.

Summary -- 7000 Series Alloys

In summary, the high strength Al-Zn-Mg-Cu alloys such as 7075 fall short of the desired properties because of poor notch toughness and poor weldability. Lower strength Al-Zn-Mg-Cu alloys such as X7002 show much better notch toughness but still lack the desired weldability. The Cu-free Al-Zn-Mg alloys such as X7006 and 7039 have good weldability and good notch toughness at room and cryogenic temperatures. At the present stage of development, however, these alloys do not meet the strength requirements of the research project. There is considerable hope for further improvement in strength and notch strength through alloy development. As shown by the data of Cook, Chadwick, and Muir, higher strengths can be obtained in more highly alloyed compositions. Research should be carried out to determine the ratios of Zn to Mg that will provide optimum notch characteristics and other properties for a given level of strengths. The effect of secondary elements (Cr, Mn, etc.) on cryogenic properties is yet to be established and may also result in important improvements. In view of these possibilities, it is recommended that an experimental program for the improvement of the Al-Zn-Mg alloys be initiated.

DISCUSSION

It is obvious from this review of the literature on the high strength aluminum alloys that none of the presently established compositions are really close to the goals of this project. Specific alloys are deficient in various ways; for example, some that have adequate strength and are relatively insensitive to notches at low temperatures are not satisfactorily weldable, while none of those that are readily weldable develop the desired strength.

Experimental approaches have been outlined(63-17) for the initial program to develop better properties and characteristics through changes in composition of present commercial alloys of 2000 and 5000 types. This program will also include a fairly broad survey of promising Al-Zn-Mg (7000) type alloys. The initial efforts will be largely empirical since the broad metallurgical principles that underlie such properties as cryogenic notch toughness and strength are as yet inadequately defined. It is anticipated that as additional information becomes available concerning effects of composition changes and heat treating variables on combinations of toughness and strength, and these data are correlated with structural examinations, a more definitive picture will emerge.

The methods selected for analyzing data will be important to determine whether progress is being made and to develop a better understanding of the relative influence of the metallurgical and structural factors involved. In this connection it is highly pertinent to refer to two recent papers prepared by Alcoa Research Laboratories(63-1, 63-12). In both cases, a simple graphical method, which has been used by other investigators for comparative analysis in the last few years, was applied to high strength aluminum alloys.

Room Temperature Notch Sensitivity

The first paper(63-12) reviewed room temperature notch properties and tear test data for commercial alloys in various tempers. The method of evaluation involved plotting notch sensitivity indices as functions of the yield strength determined on smooth specimens. The notch-tensile and notch-yield ratios obtained in room temperature tests of 2000 and 7000 series alloys employing sharp edge notched sheet specimens are shown in this manner in Figure 9. These data indicated strongly that at room temperature the 7000 type alloys exhibited a lower degree of notch sensitivity than 2000 series alloys at comparable yield strengths. The notch-tensile ratios of the 2000 series alloys tended to scatter (between 0.85 and 0.98) over the yield strength range from about 40,000 to 72,000 psi and then decreased sharply. On the other hand, the notch-yield ratios of the same alloys decreased progressively and almost linearly over the 40,000 to 72,000 psi yield strength range. Tests of these same materials and additional alloys and tempers were made employing the eccentrically notched tear specimen illustrated in Figure 10 with results for tear strength-yield ratio shown in the same Figure. These data indicated an approximately linear relationship between this ratio and yield strength for the alloys of both types, the rate of change for the two alloy types being comparable, but the 7000 group again evidencing some advantage in the combination of ratio and yield strength.

Since the data for the 2000 series alloys included tempers obtained by (1) natural aging only (-T4), (2) strain hardening prior to natural aging (-T3 type), (3) artificial aging only (-T6) and (4) strain hardening plus artificial aging (-T8 type), the data were examined for evidence that a particular sequence of these operations or a greater or lesser amount of strain hardening would be advantageous. Neither the results for edge notched or tear specimens provided evidence that a particular temper provided a superior combination of ratio and yield strength. This indicates that an increase or decrease in yield strength obtained for a given alloy by altering the thermal treatment is accompanied by a loss or gain in ratio corresponding to a shift along the appropriate line in either Figure 9 or 10. From the standpoint of progress in alloy development, it is considered that changes in composition, fabrication or thermal treatment that do nothing more than shift the combination of notch ratio and yield strength in either direction along one of these lines represent merely "treading water" and no actual accomplishment. What is needed obviously is superior combinations of strength and toughness. The room temperature data show that in this respect the 7000 group are somewhat superior to the 2000 group.

Cryogenic Temperature Notch Sensitivity

It is apparent from previous discussion that the comparative notch sensitivity ratings of these alloys at cryogenic temperatures may be different from those based on room temperature testing. From a casual examination of data, the influence of temperature on notch ratios of 7000 series alloys appears to be somewhat greater than is observed for 2000, 5000 or 6000 series alloys. This may be restated by saying that the temperature coefficient of the notch ratios for the 7000 alloys exceed those for the other series. Thus, the advantage of the 7000 group alloys over those of the 2000 group which was shown in the room temperature tests tends to disappear at -423°F because of the greater temperature coefficient.

The analysis of notch toughness versus yield strength has been extended to cryogenic temperatures in the most recent paper(63-1) from which Figures 11, 12 and 13 are reproduced. The data from -320°F tests of several commercial alloys as well as most of the newer experimental 7000 type alloys plot within a fairly narrow band when the notch-yield ratio is employed (Figure 11). The band for notch-tensile ratios is somewhat broader (Figure 12). Although fewer data are available for comparison at -423°F, a similar trend for decrease in notch-yield ratio with increasing yield strength is shown at this temperature (Figure 13).

In the same manner as indicated for analysis of room temperature data, progress in achieving superior combinations of strength and toughness at cryogenic temperatures can be measured by the displacement upwards and to the right that can be achieved in these diagrams. Manipulations of composition or temper that merely shift the combination of these properties back or forth parallel to and within the band will not represent significant progress. On the other hand, if compositions can be found that combine strengths in the range obtained with alloys 7079-T6, 7075-T6 or 7178-T6 with weldability and notch ratios at or above those indicated by the upper limit of the band, these will represent a distinct advance.

Data from an experimental alloy, designated Al-Zn-Mg in Figures 11-13 is indicative of a superior combination of strength and toughness at cryogenic temperatures. The variation in composition believed to be responsible for this significant improvement is being applied to other alloys capable of developing higher strengths that will be included in the experimental program.

The notch-yield ratios show more regular changes with yield strength and offer more consistent relative ratings among alloys than do the notch-tensile ratios, both at room temperature and cryogenic temperatures, and therefore, are considered a potentially more useful criterion of actual achievement for alloy development purposes. Although notch-tensile ratios should be plotted and analyzed, it is recommended that careful analysis of notch-yield ratios versus yield strengths be made to determine whether the experimental program is moving toward program objectives.

In the discussion of reference 60-6, Brown, Freymeyer and Rawe presented an analysis of notch tensile data which combines features of the foregoing methods with the temperature effects. The notch tensile ratios were plotted versus yield strengths for each alloy and for all testing temperatures (Figure 14). Empirically the curves connecting the points obtained at the different testing temperatures for the various alloys appeared to fit an equation of the form:

$$\frac{N}{U} = \left(\frac{Y_o}{Y}\right)^n$$

where: N = notched strength
U = unnotched tensile strength
Y = yield strength
Y_o and n are constants for each alloy

These authors' analysis of the data from reference 60-6 resulted in assignment of a value of n = 1.0 for alloys 2219-T62, 5456-H321 and 6061-T6, while n = 2.0 appeared to fit the data for 2014-T6, 7075-T6, 7079-T6 and 7178-T6. The value of n might be regarded as a temperature coefficient of the combination of notch tensile ratio and yield strength. Application of this method of analysis may have merit in evaluating the changes in properties with temperature as influenced by composition, fabricating and processing factors. Our preliminary examination of data by this method indicates values of n may vary over a considerable range for the different alloys (0.4 to 2.8). The lower values apply to the 2000 type alloys and indicate a lesser effect of temperature than the higher values which apply to alloys of the 7000 group.

It would be highly desirable to have available a reliable method for correlating the properties determined at various temperatures in order to more effectively employ -320°F tests for primary evaluations and minimize the number of -423°F tests required. Since the data from various sources indicate that results obtained at -320°F do not necessarily indicate those that may be expected at the lower temperature, the -320°F tests serve merely to screen out materials which would have no prospect of meeting the -423°F requirements. The effects of testing temperature seem to vary with composition and should be analyzed more thoroughly to develop methods of predicting the extent of change from -320 to -423°F.

Since alloys that are now used as well as those which will be investigated in the experimental program vary in density by several per cent, it appears desirable to compute and tabulate data on a strength/density basis in addition to the usual tabulation of strength values uncorrected for density differences.

Alloy Structures -- Deformation Characteristics -- Fracture Mechanisms

As previously stated the metallurgical principles required to provide a well-based fundamental approach to this problem are incompletely developed. Some effort has been made to investigate systematically the effects of temper and resulting structure on the room temperature notch toughness[63-12]. In the case of alloys 2014 and 6061, it was shown that when equal yield strengths could be produced by underaging (less aging than required for the -T6 temper) and overaging (aging extended beyond the -T6 temper), the notch toughness was superior in the underaged condition (Figure 15). The data for 7000 series alloys are less conclusive -- for example in Figures 11 and 12, X7006-W does not have an outstanding combination of toughness and strength. These relationships should be analyzed in greater detail and some systematic work undertaken to develop additional guide lines which can be applied in the program.

Some thought has been given, and should be extended, to the correlations between the fine structures of these materials and their capacity for plastic deformation and ability to redistribute localized stresses and forestall fracture. The precipitate structures of the 2000 and 7000 series alloys differ considerably. In the -T4 and -T3 type tempers, 2000 series alloys are hardened predominantly, if not entirely, by Guinier-Preston zone structure. Dislocation movement with this structure is considered to be impeded by the lattice strains associated with the zones, but is less complex than in the artificially aged tempers, -T6 or -T8 types. In the latter, the presence of transition S' (Al-Cu-Mg) precipitate platelets necessitates dislocation climb around these particles of second phase. It seems logical to expect that fracture would occur with less effective prior plastic deformation in the two-phase structure.

The 7000 series alloys in -T6 type tempers are hardened by extremely small 20-25Å spherical zones. It is thought that deformation occurs by shear of the zones which change shape as a result of the passage of dislocations. Although the precipitate structures of the 2000 alloys in -T8 type tempers are quite different from those of 7000 alloys in -T6 type tempers and dislocation movement is thought to proceed by different mechanisms, the data available to correlate strength and toughness do not indicate distinctly different behavior. There is some indication that differences of the type one might expect prevail at room temperature. The differences apparently are largely lost at cryogenic temperatures. The answers may lie partially in the differences in activation energy for glide and climb of dislocations, although considerably more complex interactions are probably involved.

The factors of grain size and shape as well as degree of recrystallization also deserve attention. Some preliminary studies have indicated that the effect of these variables on cryogenic notch toughness may be greater than would be anticipated from room temperature measurements.

Some of the recent observations concerning purely mechanical tensile fractures indicate that cracks are initiated by the formation of minute voids at constituent particles, dispersoids and precipitates as the metal sustains plastic deformation. The voids join by the separation of the metal between them to form an embryonic crack. The high stress concentration at the newly-formed crack tip accelerates the formation of additional voids at other particles for a distance of several microns ahead of the crack. The crack in turn extends to these voids and propagates by additional accelerated void formation and combination. These observations present a strong argument for a single phase structure to achieve increased resistance to fracture by elimination of void-nucleating particles. There is a significant amount of supporting experimental evidence that ductility of aluminum alloys may be improved without corresponding reductions in strength by reducing the volume fraction of the relatively non-ductile intermetallic phase particles. The effects are, of course, dependent upon the specific nature of the particle and upon size and distribution as well. Gains in elongation through reduction in the amounts of impurity elements such as iron and silicon have been adequately documented for certain alloys. The application of such approaches for improvement of toughness deserves attention but must be attacked judiciously since there are distinct hazards associated with elimination of the sparsely soluble constituents. As purity increases the tendency for recrystallization and grain growth during fabrication and heat treatment is greatly accentuated and the resulting coarse grain structures may completely offset or even outweigh the gain which would otherwise be expected. Although a portion of the experimental program might be directed toward determining the possibilities for alloy improvement associated with general reduction in impurities and insoluble constituents, it is recommended that most of the investigative work be carried out with the high grade of commercial ingot that has previously been employed in alloys for cryogenic service.

TABLES

TABLE I

MECHANICAL PROPERTIES OF WROUGHT ALUMINUM ALLOYS (6000 AND 5000 SERIES) REGISTERED WITH THE ALUMINUM ASSOCIATION

AA Number	Chemical Composition Limits(1)										Tensile Properties(2)				
	Silicon %	Iron %	Copper %	Manganese %	Magnesium %	Chromium %	Nickel %	Zinc %	Titanium %	Others %	Product Tested	Temper	T.S. Ksi	Y.S. Ksi	Elong. %
6151	0.6-1.2	1.0	0.35	0.20	0.45-0.8	0.15-0.35	--	0.25	0.15		Forging	-T6	48	43	17(3)
6061	0.40-0.8	0.7	0.15-0.40	0.15	0.8-1.2	0.15-0.35	--	0.25	0.15		Plate	-T6	45	40	17
6062	0.40-0.8	0.7	0.15-0.40	0.15	0.8-1.2	0.04-0.14	--	0.25	0.15		Plate	-T6	45	40	17
6066	0.9-1.8	0.50	0.7-1.2	0.6-1.1	0.8-1.4	0.40	--	0.25	0.20		Extrusion	-T6	57	52	12
6071	1.1-1.9	0.50	0.15-0.40	0.40-1.0	0.8-1.4	0.10	--	0.25	0.15		Sheet	-T6	57	52	10(4)
5154	0.45 Si +	Fe	0.10	0.10	3.1-3.9	0.15-0.35	--	0.20	0.20		Plate	-H34	42	33	13
5454	0.40 Si +	Fe	0.10	0.50-1.0	2.4-3.0	0.05-0.20	--	0.25	0.20		Plate	-H34	44	35	10
5456	0.40 Si +	Fe	0.10	0.50-1.0	4.7-5.5	0.05-0.20	--	0.25	0.20		Plate	-H343	56	43	?(3)
5083	0.40	0.40	0.10	0.30-1.0	4.0-4.9	0.05-0.25	--	0.25	0.15		Plate	-H343	52	41	?(3)
5086	0.40	0.50	0.10	0.20-0.7	3.5-4.5	0.05-0.25	--	0.25	0.15		Plate	-H34	47	37	10

(1) Composition in percent maximum unless shown as a range or a nominal value.

(2) Standards for Wrought Aluminum Mill Products - The Aluminum Association (unless indicated otherwise).

(3) Alcoa Aluminum Handbook.

(4) Alcoa Aluminum Alloys 6070 and 6071 - Green Letter.

TABLE II

NOTCH SENSITIVITY AND CRYOGENIC PROPERTIES OF Al-Mg ALLOYS

		Properties of Plate					Properties of Welded Joints					
Alloy and Temper	Temp. °F	Tensile Strength Ksi	0.2% Yield Strength Ksi	Elong. in 2" %	Sharp Notch Tensile Strength Ksi*	Notch Tensile Ratio	Tensile Strength Ksi	Joint Efficiency %	Elong. in 2" %	Sharp Notch Tensile Strength Ksi*	Notch Tensile Ratio	Reference
5086-O	75	39.9	16.2	25	46.9	1.18						(61-34)
	-320	56.8	18.2	43	55.9	0.98						
	-423	80.5	20.7	40	60.0	0.75						
5086-H34	75	50.3	38.6	10	63.2	1.26						(61-34)
	-320	68.3	45.0	25	75.9	1.11						
	-423	93.5	48.9	27	73.1	0.78						
5454-O	75	37.4	17.9	21	48.3	1.29						(61-34)
	-320	56.4	21.6	38	58.2	1.03						
	-423	81.1	23.9	38	61.8	0.76						
5454-H34	75	41.9	32.8	13	58.6	1.40						(61-34)
	-320	61.7	40.0	31	70.5	1.14						
	-423	87.8	41.0	33	75.8	0.86						
5083-O	75	46.8	20.2	20	48.8	1.04	43.2	92	14	43.7	1.01	(61-34)
	-320	63.0	22.5	36	57.0	0.90	62.4	99	24	51.6	0.83	
	-423	85.2	25.2	32	59.3	0.70	64.6	76	12	49.8	0.77	
5083-H113	75	48.6	34.9	16	61.2	1.26	43.7	90	15	44.5	1.02	(61-34)
	-320	65.4	40.8	31	70.2	1.07	62.4	95	20	52.8	0.85	
	-423	90.0	41.8	30	72.8	0.81	64.2	71	11	51.5	0.80	
5456-O	75	50.4	23.2	17	50.4	1.00	46.7	93	15	44.6	0.95	(61-34)
	-320	67.2	25.7	32	60.6	0.90	60.3	90	15	50.9	0.84	
	-423	84.5	28.6	25	59.9	0.71	62.4	74	9	47.5	0.76	
5454-H321	75	54.5	35.0	13	58.5	1.07	46.2	85	13	44.7	0.97	(61-34)
	-320	73.4	38.3	24	68.1	0.93	60.7	83	12	51.0	0.84	
	-423	96.2	43.9	22	71.2	0.74	58.2	61	6	49.1	0.84	

TABLE II (CONTINUED)

NOTCH SENSITIVITY AND CRYOGENIC PROPERTIES OF Al-Mg ALLOYS

Alloy and Temper	Temp. °F	Properties of Sheet: Tensile Strength Ksi	0.2% Yield Strength Ksi	Elong. in 2" %	Notch Tensile Strength Ksi*	Notch Tensile Ratio	Properties of Welded Joints: Tensile Strength Ksi	Joint Efficiency %	Elong. in 2" %	Notch Tensile Strength Ksi*	Notch Tensile Ratio	Reference
5086-H34	78	47.8	35.7	9	48.7	1.02	39.0	82	4			(61-10)
	-100	48.9	36.6	15	50.3	1.03	39.5	81	5			
	-320	65.4	40.8	24	61.9	0.95	56.4	86	9			
	-423	95.3	47.0	30	71.4	0.75	75.3	79	11			
5086-H38	78	64.2	58.2	7	64.6	1.01						(61-10)
	-100	66.2	58.4	10	67.5	1.02						
	-320	76.8	60.9	18	75.3	0.98						
	-423	105.0	75.6	25	81.1	0.77						
5083-H38	78	62.7	56.7	5	62.1	0.99						(61-10)
	-320	82.1	65.0	15	76.9	0.94						
	-423	101.0	71.5	13	87.1	0.86						
5154-H38	78	47.6	40.2	9	49.5	1.04	35.7	75	3			(61-10)
	-100	49.3	40.8	14	51.2	1.04	38.6	78	2			
	-320	66.2	47.1	30	64.3	0.97	55.5	84	7			
	-423	93.5	54.0	35	77.6	0.83	75.8	81	11			
5456-H321	75	57.4	39.5	14.5	47.6	0.83	51.9	91	13	54.4	1.05	(63-16)
	-320	76.6	46.7	26.8	52.7	0.69	63.7	83	15.8	59.7	0.93	
	-423	96.4	52.6	21.7	56.7	0.59	59.1	62	3.8	59.7	1.01	
5456-H343	75	58.2	46.1	8.3	48.7	0.84	51.9	90	7	53.2	1.03	(63-16)
	-320	77.1	51.4	18.5	53.3	0.69	59.1	77	6.5	59.0	1.00	
	-423	82.3	56.8		59.0	0.72	58.8	72	3.0	59.9	1.02	

* K_t = 13.5 to 15, Cylindrical Specimens, for alloys referenced (61-34)
K_t = 6.3 for alloys referenced (61-10)
K_t > 17 for alloys referenced (63-16)

All specimens parallel to direction of rolling.

TABLE III

MECHANICAL PROPERTIES OF WROUGHT ALUMINUM ALLOYS (2000 SERIES)
REGISTERED WITH THE ALUMINUM ASSOCIATION 1963

AA Number	Chemical Composition Limits(1) Silicon %	Iron %	Copper %	Manganese %	Magnesium %	Chromium %	Nickel %	Zinc %	Titanium %	Others %	Product Tested	Tensile Properties(2) Temper	T.S. Ksi	Y.S. Ksi	Elong. %
2014	0.5-1.2	1.0	3.9-5.0	0.4-1.2	0.20-0.8	0.10	--	0.25	0.15	--	Forging	-T6	70	60	13
2017	0.8	1.0	3.5-4.5	0.40-1.0	0.20-0.8	0.10	--	0.25	--	--	Rod	-T4	62	40	22
2018	0.9	1.0	3.5-4.5	0.20	0.45-0.9	0.10	1.7-2.3	0.25	--	--	Forging	-T61	61	46	12
2020	0.40	0.40	4.0-5.0	0.30-0.8	0.03	--	--	0.25	0.10	0.9-1.7 Li**	Sheet	-T6	86	79	6
2024	0.50	0.50	3.8-4.9	0.30-0.9	1.2-1.8	0.10	--	0.25	--	--	Plate	-T3	70	50	18
											Plate	-T4	68	47	19
											Plate	-T6	69	57	10(3)
											Sheet	-T81	70	65	6(3)
											Sheet	-T86	75	71	6(3)
2025	0.50-1.2	1.0	3.9-5.0	0.40-1.2	0.05	0.10	--	0.25	0.15	--	Forging	-T6	58	37	19
2218	0.9	1.0	3.5-4.5	0.20	1.2-1.8	0.10	1.7-2.3	0.25	--	--	Forging	-T71	50	40	11
*2219	0.20	0.30	5.8-6.8	0.20-0.40	0.02	--	--	0.10	0.02-0.10	0.10-0.25 Zr⁄	Plate	-T62	60	42	10(4)
											Plate	-T81	66	51	11(4)
											Plate	-T87	69	57	10(4)
2618	0.25	0.9-1.3	1.9-2.7	--	1.3-1.8	--	0.9-1.2	--	0.04-0.10	--	Forging	-T61	64	54	10
Alcoa 27S† (Discontinued)	0.8		4.5	0.8						0.05 Sn		-T6	60	50	9

*Composition - Alcoa Aluminum Handbook
**Also 0.10 - 0.35% Cd
⁄Also 0.05 - 0.15% V
†Nominal Composition

(1) Composition in percent maximum unless shown as a range or a minimum. Unless otherwise noted, all compositions obtained from the Aluminum Assn.

(2) The Aluminum Assn. Standards for Wrought Aluminum Mill Products (unless noted otherwise).

(3) The Alcoa Aluminum Handbook.

(4) Alcoa Aluminum Alloy 2219 - Green Letter.

TABLE IV

NOTCH SENSITIVITY AND CRYOGENIC PROPERTIES OF Al-Cu ALLOYS

Alloy and Temper	Temp. °F	Properties of Sheet: Tensile Strength Ksi	0.2% Yield Strength Ksi	Elong. in 2" %	Notch Tensile Strength Ksi*	Notch Tensile Ratio	Properties of Welded Joints: Tensile Strength Ksi	Joint Efficiency %	Elong. in 2" %	Reference
2014-T6	78	73.1	65.7	11.0	74.5	1.02	53.1	73	2.0	(62-8)
	-100	76.4	69.3	12.0	79.2	1.04	56.7	74	2.0	
	-320	87.1	74.4	14.0	85.5	0.98	61.9	71	1.0	
	-423	104.0	86.2	17.0	97.8	0.94	75.6	73	1.2	
2020-T6	75	81.0	75.4	7.0	35.0	0.43				Alcoa Data
2024-T3	78	67.9	47.4	18.0	60.2	0.89				(62-8)
	-100	70.2	48.9	21.0	61.2	0.87				
	-320	87.0	60.9	22.0	76.2	0.88				
	-423	110.0	73.1	17.0	88.8	0.81				
2024-T4	78	67.7	42.8	19.0	59.0	0.87				(62-8)
	-100	69.8	43.7	22.0	60.7	0.87				
	-320	84.9	54.1	27.0	71.9	0.81				
	-423	107.0	73.3	16.0	88.3	0.83				
2024-T86	75	75.8	71.3	5.2	51.3	0.68				Alcoa Data
	-320	91.2	83.5	8.0	47.0	0.52				
2219-T62	70	60.9	44.1	12.0	56.5	0.93	50.6	83		(61-36)
	-110	66.5	50.2	11.2	56.8	0.88	46.5	71		
	-320	77.9	54.3	14.5	67.1	0.86	61.3	78		
	-423	92.3	59.1	18.0	72.8	0.79	66.6	72		
2219-T81	70	64.6	51.5	10.7	62.4	0.97	47.0	72		(61-36)
	-110	69.7	55.9	9.5	64.9	0.93				
	-320	81.8	63.2	12.7	73.4	0.94	58.8	71		
	-425	96.9	68.5	15.3	79.9	0.82	64.8	67		

TABLE IV (CONTINUED)

NOTCH SENSITIVITY AND CRYOGENIC PROPERTIES OF Al-Cu ALLOYS

		Properties of Sheet					Properties of Welded Joints			
Alloy and Temper	Temp. °F	Tensile Strength Ksi	0.2% Yield Strength Ksi	Elong. in 2" %	Notch Tensile Strength Ksi*	Notch Tensile Ratio	Tensile Strength Ksi	Joint Efficiency %	Elong. in 2" %	Reference
2219-T87	78	70.7	58.2	9.0	69.7	0.99	51.1	72	2	(62-8)
	-100	76.4	62.4	9.0	74.6	0.98	49.5	65	4	
	-320	88.4	69.7	11.0	85.5	0.97	61.2	69	2	
	-423	104.0	76.4	14.0	95.6	0.92	73.0	70	1	
2618-T6	70	58.2	52.1	8.7	59.7	1.03	49.2	84		(61-36)
	-110	61.9	55.3	9.2	57.5	0.93	52.8	86		
	-320	73.6	62.8	14.0	69.9	0.95	58.6	81		
	-423	87.0	66.4	18.5	75.1	0.86	65.7	76		
2618-T62	70	59.1	51.2	8.0	59.2	1.00	49.2	84		(61-36)
	-110	61.1	50.9	8.0	60.7	0.99	50.0	82		
	-320	73.4	57.6	11.6	65.4	0.89	59.9	82		
	-423	86.6	63.1	17.8	70.9	0.82	66.7	77		

* K_t = 6.3 for alloys referenced (62-8)
K_t = 8.0 for alloys referenced (61-36)
$K_t \bar{>}$ 17 for Alcoa Data

All specimens parallel to direction of rolling.

TABLE V

TENSILE PROPERTIES OF "CONSTRUCTAL" TYPE ALLOYS

Alloy	Zinc %	Magnesium %	Manganese %	Chromium %	Tensile Properties T.S. Ksi	Tensile Properties Y.S. Ksi	Tensile Properties Elong. %	Weld Properties(3) T.S. Ksi	Weld Properties(3) Y.S. Ksi	Weld Properties(3) Elong. %
AlZnMg 1	4.8	1.4	0.3	0.15	53	44	13	48	36	5.5
AlZnMg 3	4-5.5	2-3.5	.1-.6	.1-.3	65	53	10			

(1) Nominal Composition

(2) DIN 1745 (1956)

(3) Aged 3 months at room temperature; Welded with Al-5 Mg filler wire.

TABLE VI

MECHANICAL PROPERTIES OF WROUGHT ALUMINUM ALLOYS (7000 SERIES)
REGISTERED WITH THE ALUMINUM ASSOCIATION, 1963

AA Number	Chemical Composition Limits[1] Silicon %	Iron %	Copper %	Manganese %	Magnesium %	Chromium %	Nickel %	Zinc %	Titanium %	Others %	Typical Tensile Properties[2] Product Tested	Temper	T.S. Ksi	Y.S. Ksi	Elong. %
					Al-Zn-Mg Alloys										
X7003	0.35	0.35	0.10	0.10-0.50	0.9-1.6	0.05-0.20		4.3-5.3	0.20						
X7005	0.35 Si + Fe		0.10	0.20-0.7	0.7-1.8	0.05-0.20		4.0-5.0	0.15		Sheet	-T6	51	42	13[3]
X7006	0.35 Si + Fe		0.10	0.50	1.7-2.8	0.30		3.7-4.8	0.15		Plate	-T6	61	55	13[3]
X7038				.50*	3.5*			4.5*							
7039	0.30	0.40	0.25	0.10-0.40	2.3-3.3	0.15-0.25		3.5-4.5	0.10		Plate Plate	-T61 -T6	60 65	50 55	14[4] 13[4]
					Al-Zn-Mg-Cu Alloys										
7001	0.35	0.40	1.6-2.6	0.20	2.6-3.4	0.18-0.40		6.8-8.0	0.20		Rod	-T6	98	91	9
X7002	0.20	0.40	0.50-1.0	0.05-0.30	2.0-3.0	0.10-0.30		3.0-4.0	0.15		Plate	-T6	67	57	12[4]
7075	0.50	0.7	1.2-2.0	0.30	2.1-2.9	0.18-0.40		5.1-6.1	0.20		Plate	-T6	83	73	11
7076	0.40	0.6	0.3-1.0	0.3-0.8	1.2-2.0			7.0-8.0	0.20		Forging	-T6	70	60	14[3]
7277	0.50	0.7	0.8-1.7		1.7-2.3	0.18-0.35		3.7-4.3	0.10						
7178	0.50	0.7	1.6-2.4	0.30	2.4-3.1	0.18-0.40		6.3-7.3	0.20		Plate	-T6	88	78	10
7079	0.30	0.40	0.4-0.8	0.10-0.30	2.9-3.7	0.10-0.25		3.8-4.8	0.10		Plate	-T6	78	68	14

*Nominal Composition

(1) Compositions in percent maximum unless shown as a range or noted nominal.

(2) The Aluminum Assn. Standards for Wrought Aluminum Mill Products (unless noted otherwise).

(3) Alcoa Data.

(4) 7039 Metal Working News, April 1963; Iron Age, July 18, 1963.
7002 Metal Progress, October 1962.

TABLE VII

NOTCH SENSITIVITY AND CRYOGENIC PROPERTIES OF Al-Zn-Mg ALLOYS

Alloy and Temper	Temp. °F	Longitudinal Tensile Strength Ksi	Longitudinal 0.2% Yield Strength Ksi	Longitudinal Elong. in 2" %	Longitudinal Notch Tensile Strength Ksi*	Longitudinal Notch Tensile Ratio	Longitudinal Notch Yield Ratio	Long Transverse Tensile Strength Ksi	Long Transverse 0.2% Yield Strength Ksi	Long Transverse Elong. in 2" %	Long Transverse Notch Tensile Strength Ksi*	Long Transverse Notch Tensile Ratio	Long Transverse Notch Yield Ratio	Reference
X7002-T6	75	69.8	61.8	11.5	66.8	0.96	1.08	69.3	59.6	10.8	65.1	0.94	1.09	(63-1)
	-112							76.3	64.6	15.0	68.8	0.90	1.07	
	-320							87.7	72.4	15.5	58.4	0.67	0.81	
X7005-T6	75	52.0	45.7	13.8	52.2	1.00	1.17	52.2	44.8	11.8	52.2	1.00	1.17	(63-1)
	-112							60.7	50.5	12.5	58.1	0.96	1.15	
	-320							70.4	55.1	16.8	62.2	0.88	1.13	
X7006-W	75	57.5	40.6	20.8	50.0	0.87	1.23	57.6	38.4	18.5	49.6	0.86	1.29	(63-1)
	-112							60.3	40.9	19.0	51.2	0.85	1.25	
	-320							74.8	45.5	26.5	53.6	0.72	1.17	
X7006-T6	75	66.3	60.6	11.2	66.2	1.00	1.09	65.2	58.6	10.5	63.8	0.98	1.09	(63-1)
	-112							73.4	65.4	13.0	66.4	0.90	1.02	
	-320							83.9	70.4	15.0	57.0	0.68	0.81	
	-423							93.7	70.2	14.8	55.8	0.60	0.79	
X7006-T63	75	59.6	51.8	12.2	59.2	0.99	1.14	58.8	50.4	11.2	56.7	0.96	1.13	(63-1)
	-112							64.7	55.0	11.0	60.3	0.93	1.10	
	-320							77.5	59.7	18.5	60.0	0.78	0.99	
	-423							90.1	61.6	23.7	57.9	0.64	0.94	
X7039-T6	75	63.0	54.8	11.8	61.0	0.97	1.11	63.0	54.2	11.0	60.2	0.96	1.11	(63-1)
	-112							68.3	57.5	11.0	61.8	0.90	1.08	
	-320							80.8	64.3	14.0	56.8	0.70	0.88	
	-423							92.7	65.5	17.5	60.4	0.65	0.92	

* $K_t \geq 17$

TABLE VIII

EFFECTS OF CRYOGENIC TEMPERATURES ON THE PROPERTIES OF HIGH STRENGTH Al-Zn-Mg-Cu ALLOYS AND WELDMENTS

Alloy and Temper	Temp. °F	Longitudinal Tensile Strength Ksi	Longitudinal 0.2% Yield Strength Ksi	Longitudinal Elong. in 2" %	Longitudinal Notch Tensile Strength Ksi*	Longitudinal Notch Tensile Ratio	Transverse Tensile Strength Ksi	Transverse 0.2% Yield Strength Ksi	Transverse Elong. in 2" %	Transverse Notch Tensile Strength Ksi*	Transverse Notch Tensile Ratio	Reference
					Parent Metal							
X7002-T6	75	69.8	61.8	11.5	66.8	0.96	69.3	59.6	10.8	65.1	0.94	(63-1)
	-112						76.3	64.6	15.0	68.8	0.90	
	-320						87.7	72.4	15.5	58.4	0.67	
7075-T6	75	82.1	74.4	11.2	68.4	0.83	83.7	71.8	13.0	60.5	0.72	(60-6)
	-320	100.2	91.0	14.3	42.5	0.42	101.0	86.7	7.2	41.9	0.42	
	-423	113.2	105.2	6.3	40.4	0.36	116.5	101.5	6.2	37.4	0.32	
7079-T6	75	77.5	72.3	11.5	70.8	0.92	79.3	71.4	11.3	61.5	0.78	(60-6)
	-320	94.8	85.6	14.3	60.5	0.64	95.2	81.0	12.8	43.7	0.46	
	-423	114.9	95.5	15.8	59.6	0.57	112.5	90.9	9.5	43.4	0.39	
7178-T6	75	90.0	83.6	12.2	51.8	0.58	91.4	79.2	12.5	46.9	0.52	(60-6)
	-320	107.7	99.6	9.5	35.5	0.33	110.3	93.8	5.8	33.7	0.31	
	-423	123.1	111.6	8.2	31.5	0.26	130.0	112.2	4.2	32.0	0.25	
					Welded Metal							
7075-T6	75	46.5	45.0	1.0	43.6	0.94	47.2	47.0	3.0			(60-6)
	-320	52.3	51.6	1.0	42.2	0.81	56.4	53.5	1.5			
	-423	65.1	**		39.8	0.61	69.1	65.3	1.0			
7079-T6	75	50.7	42.3	1.5	52.9	1.04	49.9	42.1	1.3	55.3	1.10	(60-6)
	-320	57.2	54.3	1.2	59.2	1.03	57.0	54.8	1.4	57.0	1.00	
	-423	57.2		0.7	63.2	1.11	63.6	62.3	1.0	49.4	0.78	
7178-T6	75	54.1	51.0	1.3	53.0	0.98	46.8	**		49.6	1.06	(60-6)
	-320	53.4	**		59.5	1.12	54.3	**		54.1	0.99	
	-423	55.6	**		49.8	0.90	56.4	**		44.5	0.79	

* $K_t > 17$

** Fractured at less than 0.2% Offset

FIGURES

Mechanical Properties of Al-Mg-Si Alloys of Commercial Purity (Harris & Varley)
Dashed Lines Indicate Limits of Solid Solution

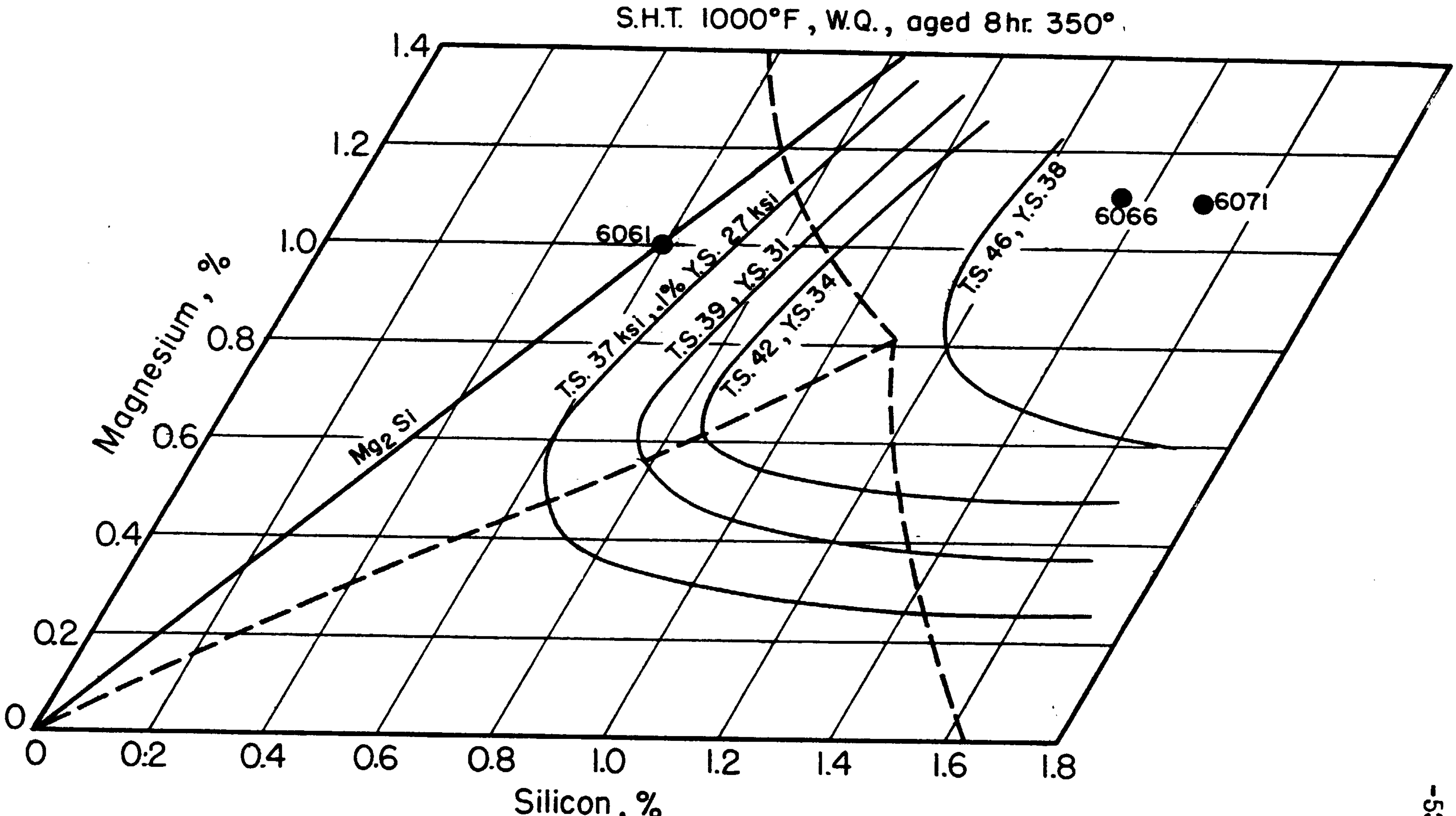


FIGURE 1

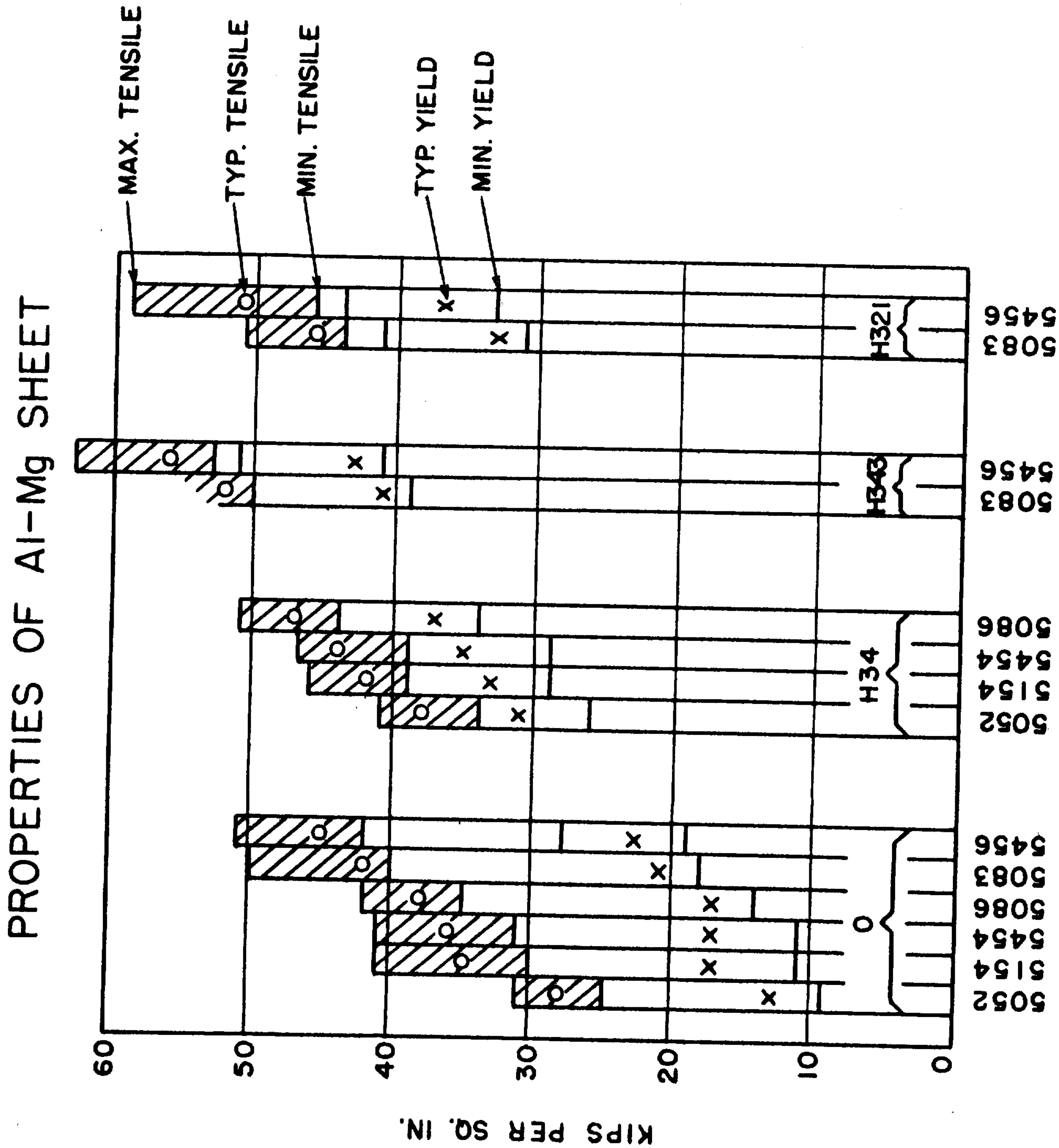

PROPERTIES OF Al-Mg SHEET
MAX. TENSILE
TYP. TENSILE
MIN. TENSILE
TYP. YIELD
MIN. YIELD
KIPS PER SQ. IN.
0
10
20
30
40
50
60
5052
5154
5454
5086
5083
5456
O
H34
H343
H321

FIGURE 2

TENSILE PROPERTIES OF 0.5" THICK ALUMINUM - MAGNESIUM - MANGANESE PLATE IN -O TEMPER

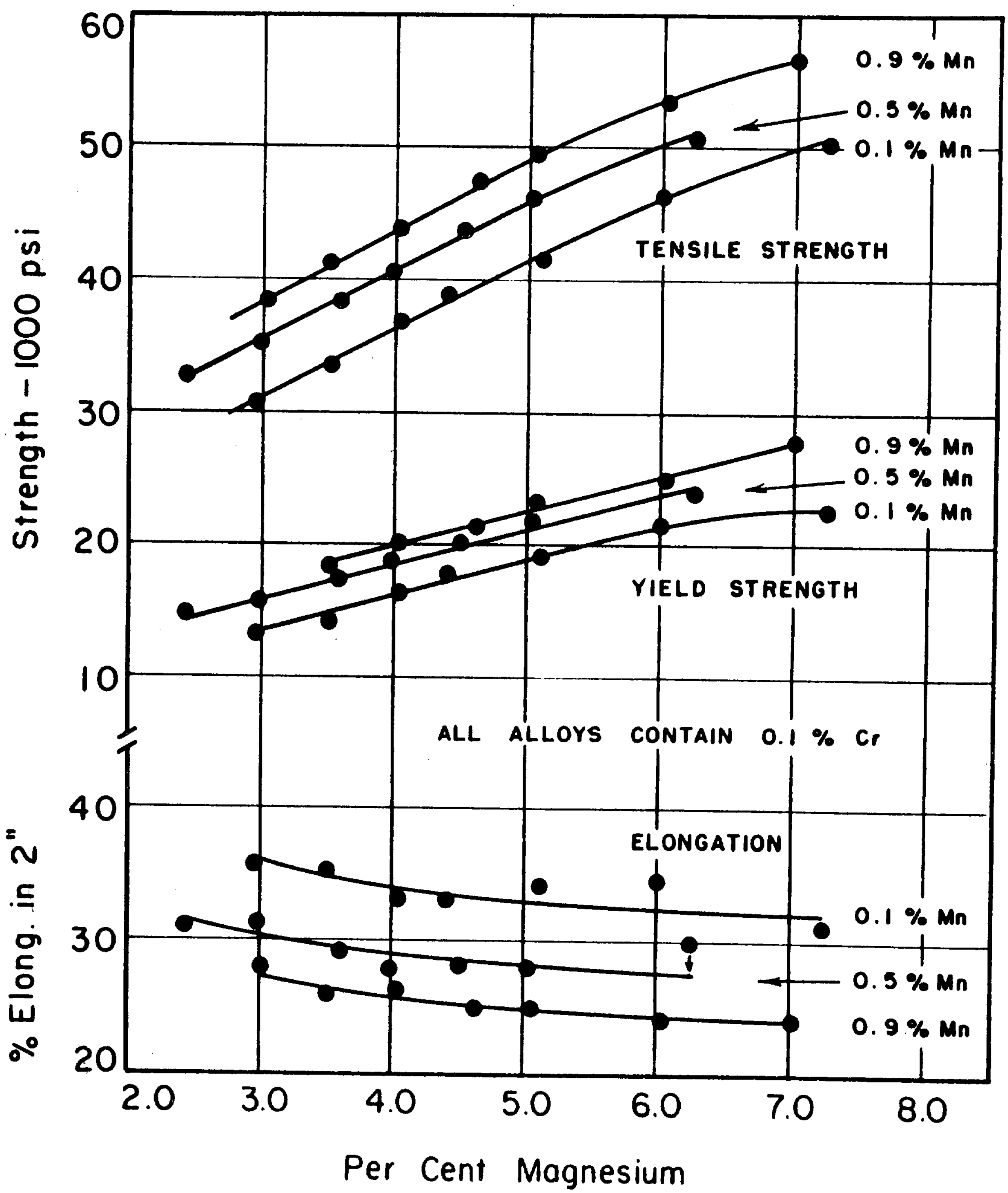


FIGURE 3

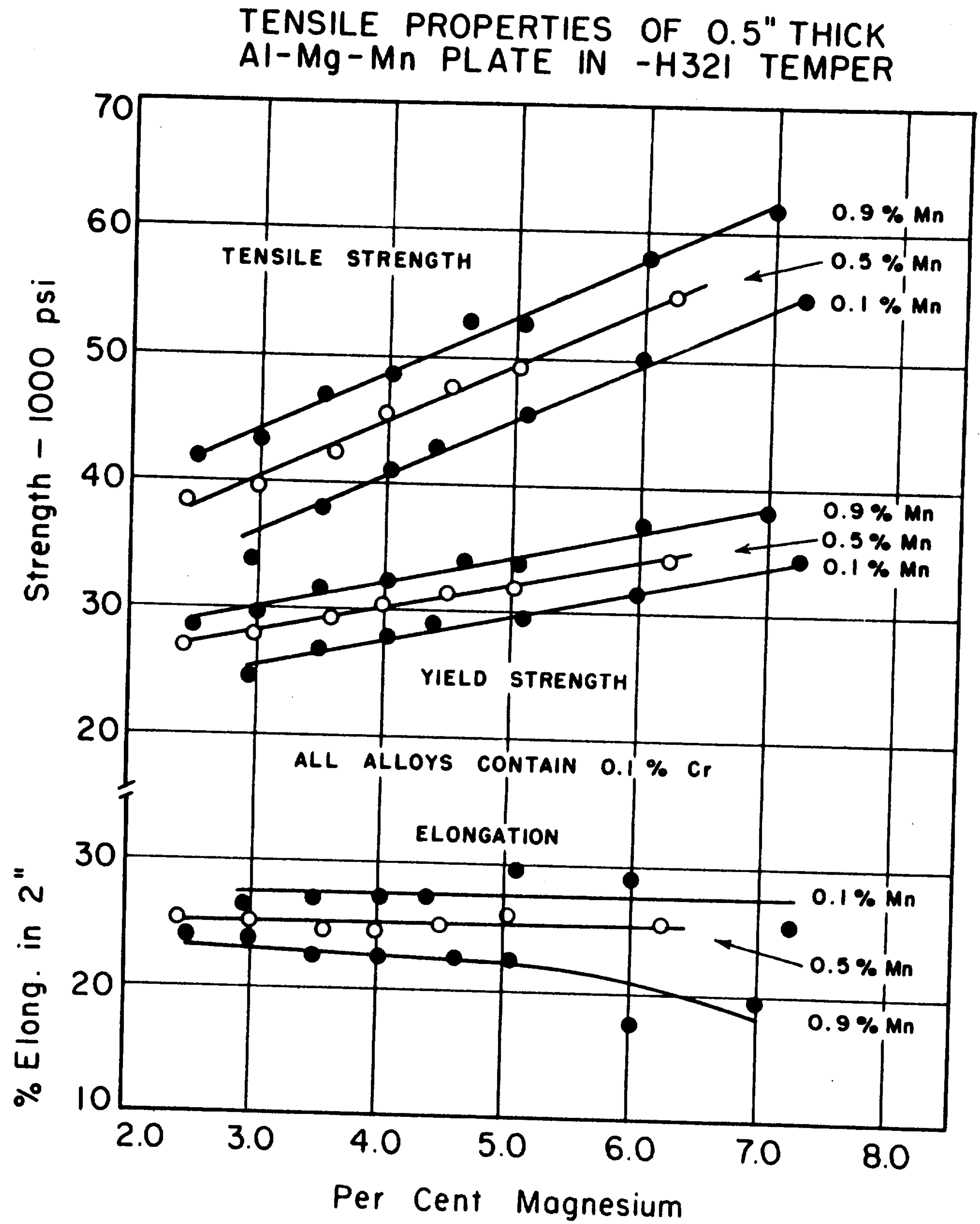

TENSILE PROPERTIES OF 0.5" THICK
Al-Mg-Mn PLATE IN -H321 TEMPER
TENSILE STRENGTH
YIELD STRENGTH
ALL ALLOYS CONTAIN 0.1 % Cr
ELONGATION
0.9 % Mn
0.5 % Mn
0.1 % Mn
Strength - 1000 psi
% Elong. in 2"
Per Cent Magnesium
70
60
50
40
30
20
10
2.0
3.0
4.0
5.0
6.0
7.0
8.0

FIGURE 4

TENSILE PROPERTIES OF 0.5" THICK Al-Mg-Mn PLATE IN -H14 TEMPER

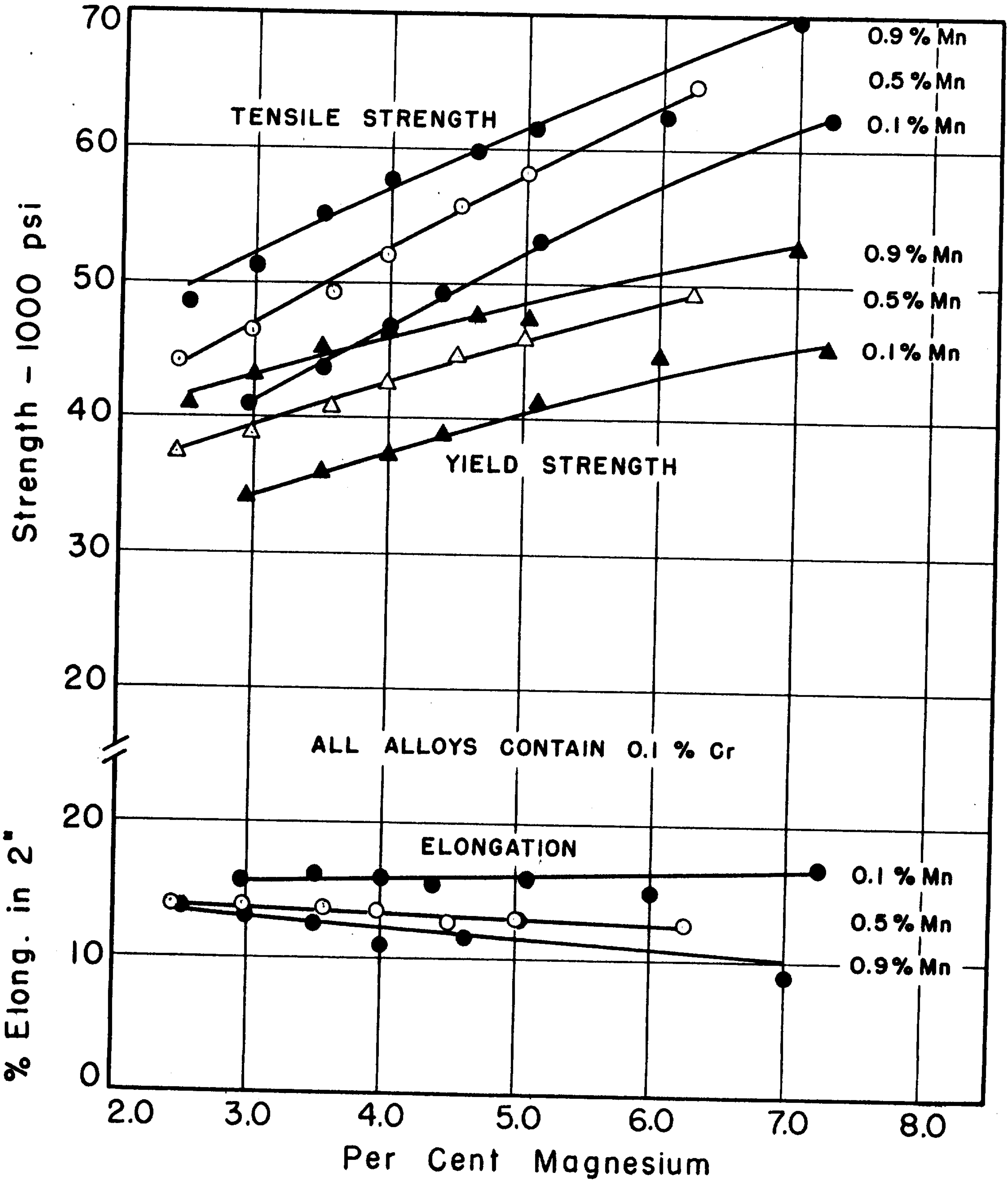


FIGURE 5

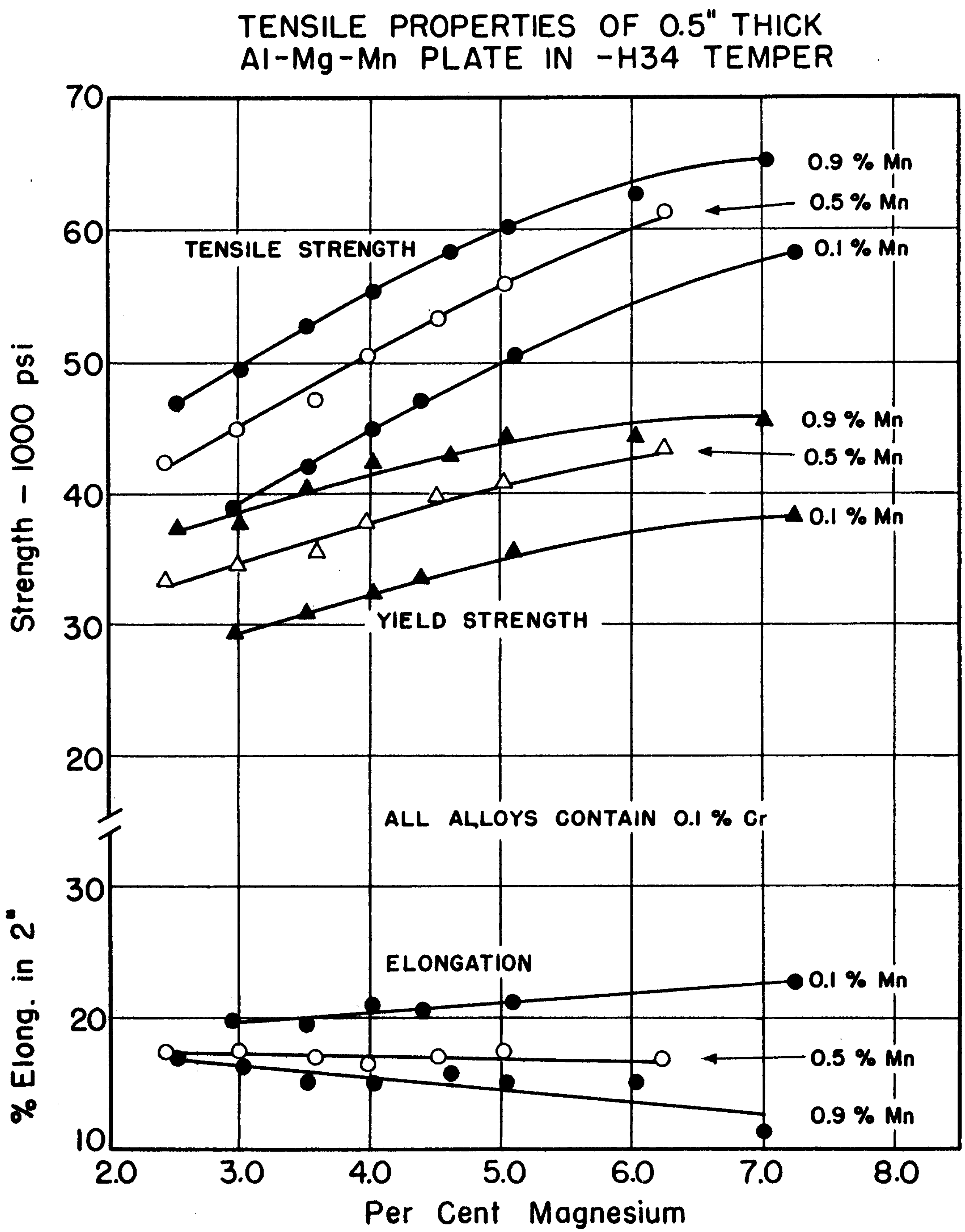

TENSILE PROPERTIES OF 0.5" THICK
Al-Mg-Mn PLATE IN -H34 TEMPER
TENSILE STRENGTH
YIELD STRENGTH
ELONGATION
ALL ALLOYS CONTAIN 0.1 % Cr
0.9 % Mn
0.5 % Mn
0.1 % Mn
0.9 % Mn
0.5 % Mn
0.1 % Mn
0.1 % Mn
0.5 % Mn
0.9 % Mn
Strength - 1000 psi
% Elong. in 2"
70
60
50
40
30
20
30
20
10
2.0
3.0
4.0
5.0
6.0
7.0
8.0
Per Cent Magnesium

FIGURE 6

Tensile Strength, Notched Tensile Strength and Notch Tensile Ratios of 5000 Type Alloys (-H3 Type Tempers) at -423°F in Relation to Mg Content

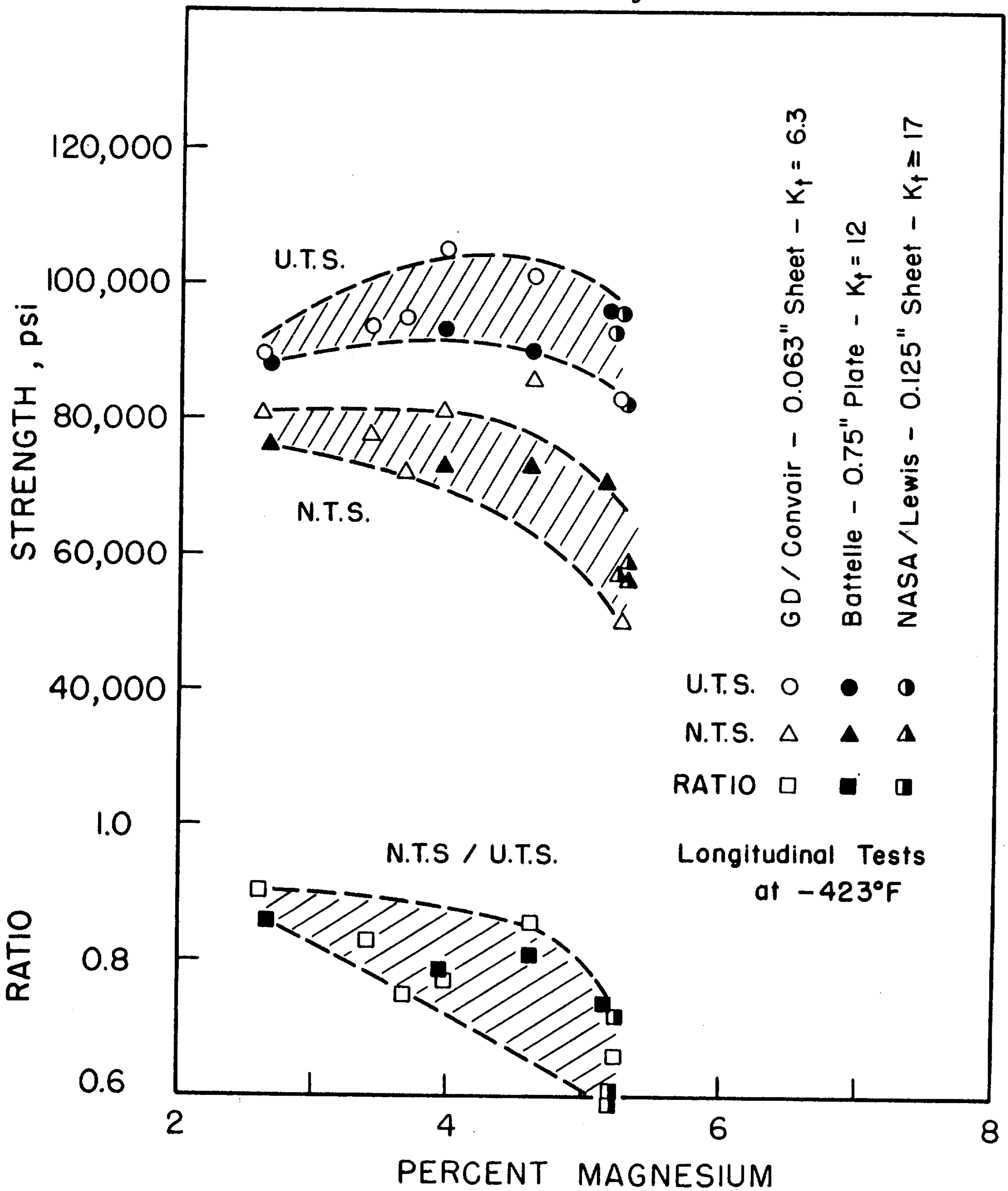
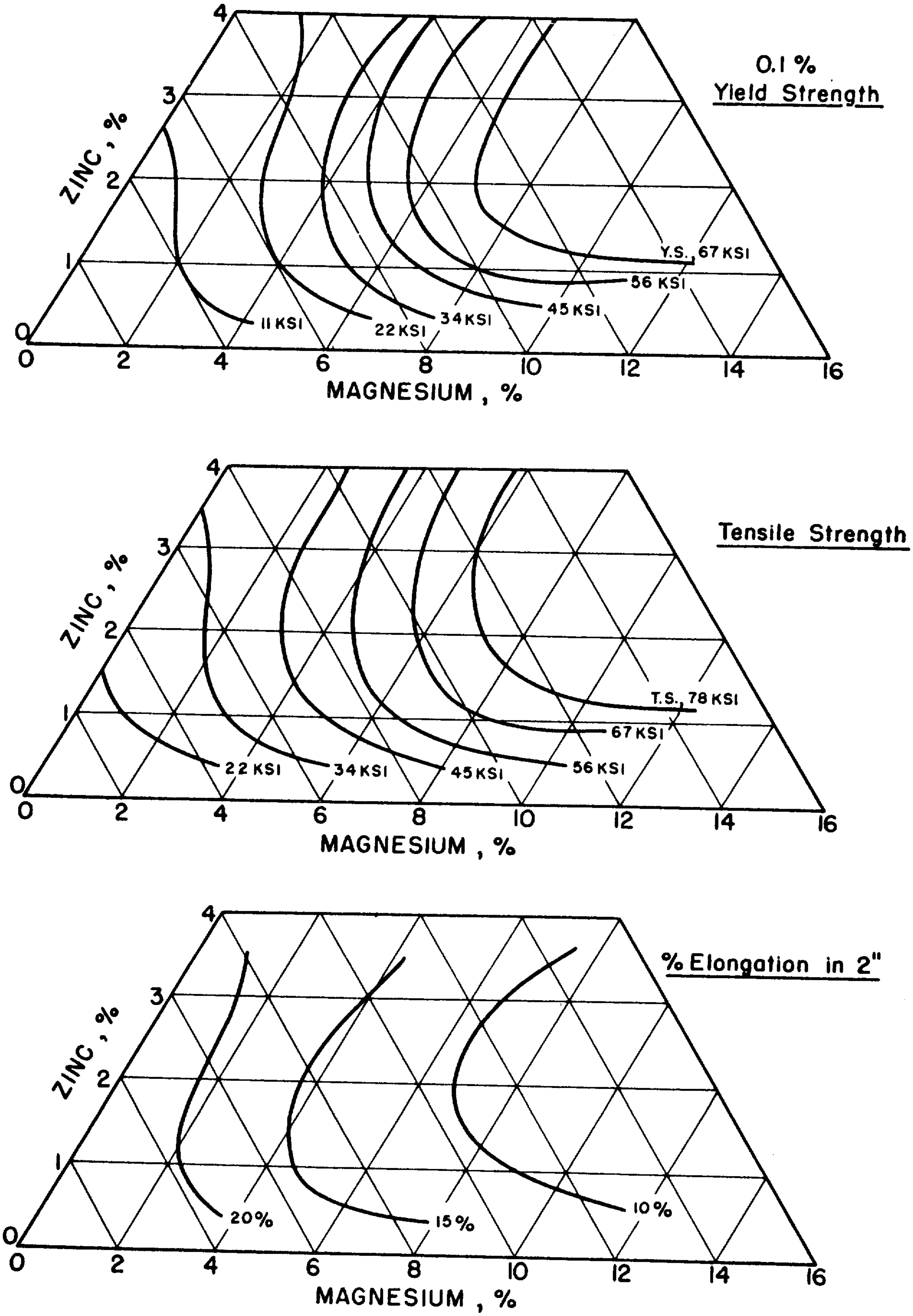


FIGURE 7



Tensile Properties of Al-Zn-Mg Alloys of Commercial Purity with 0.02 % Cu
(Cook, Chadwick, and Muir)
FIGURE 8

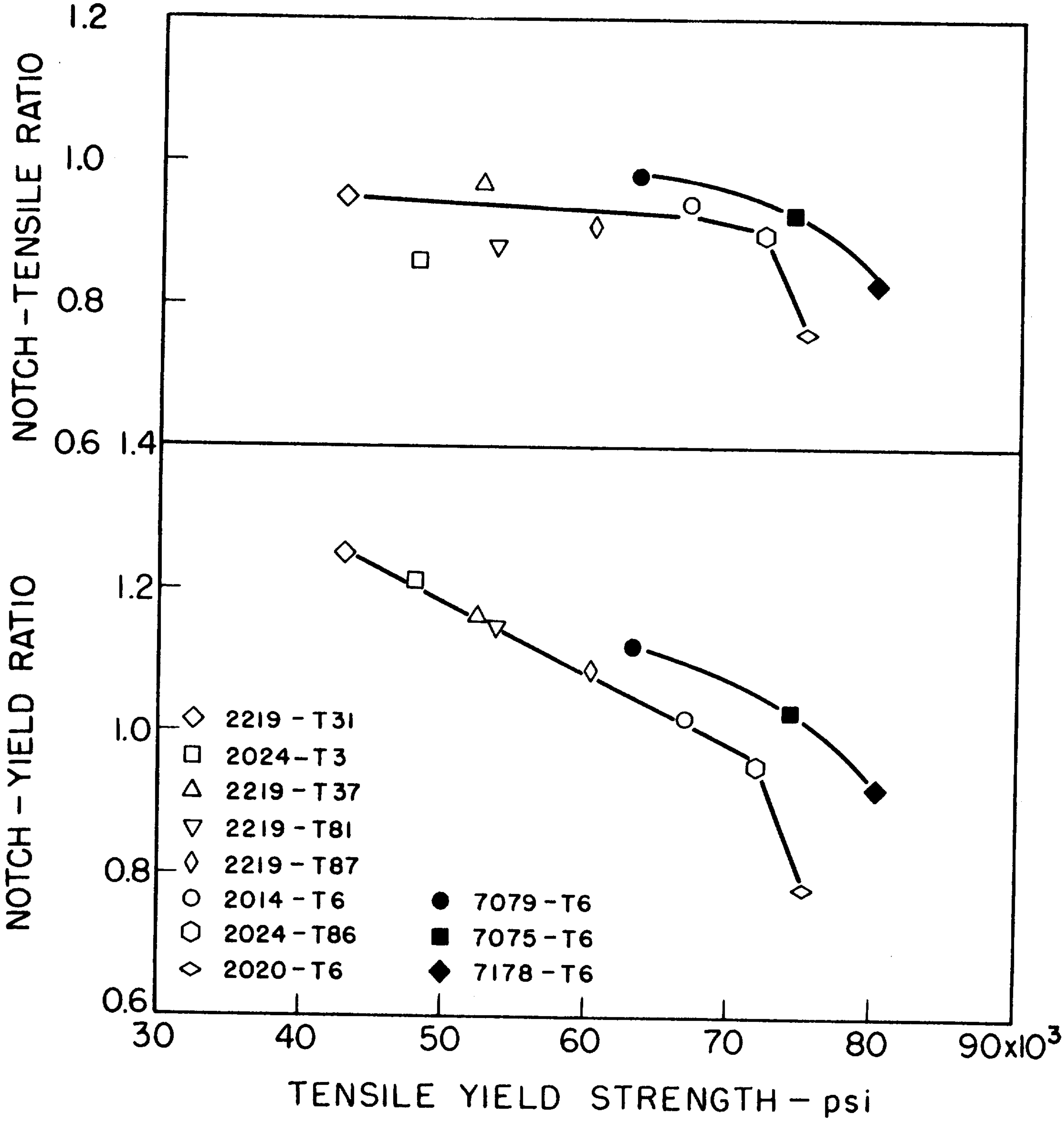
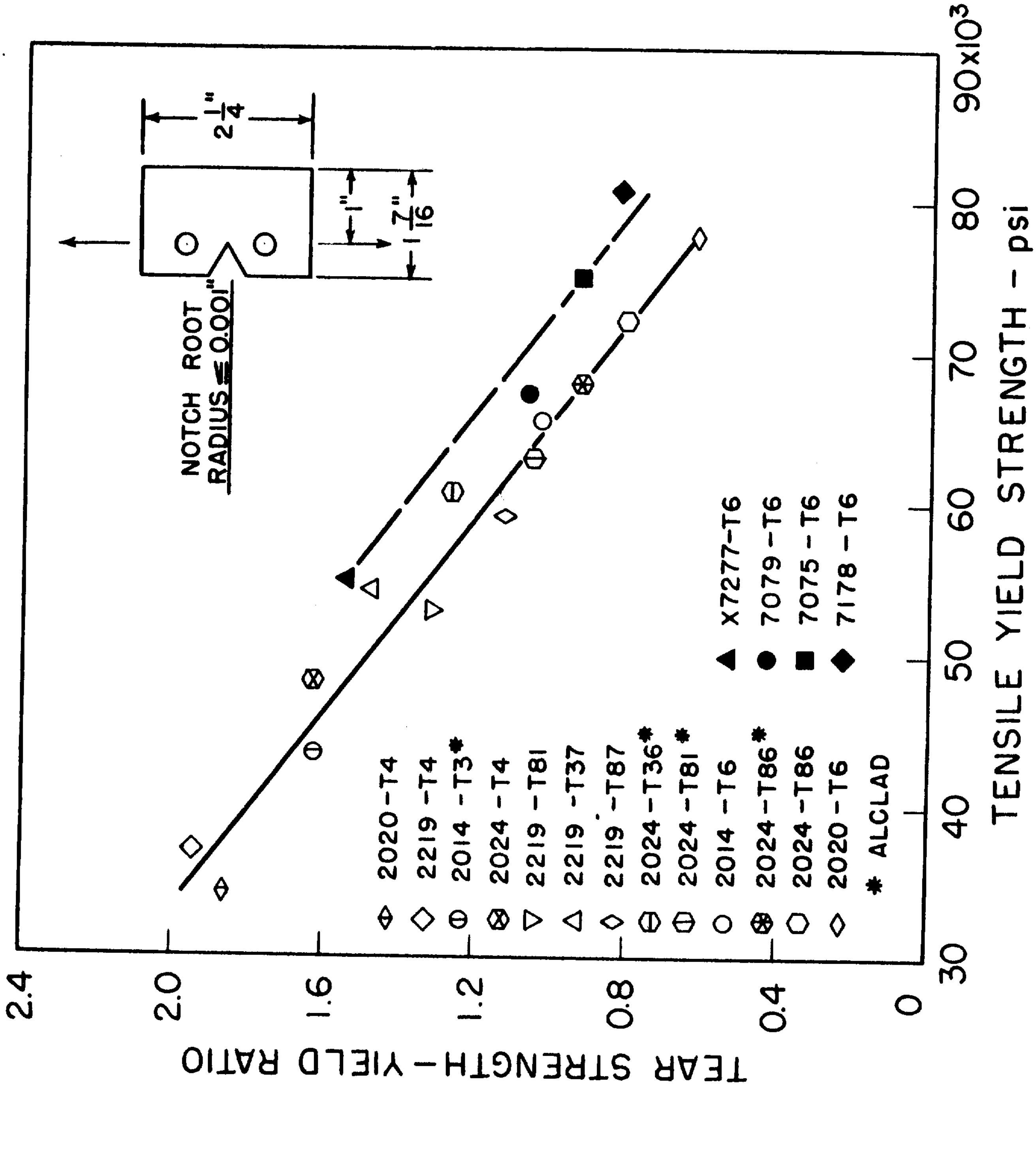
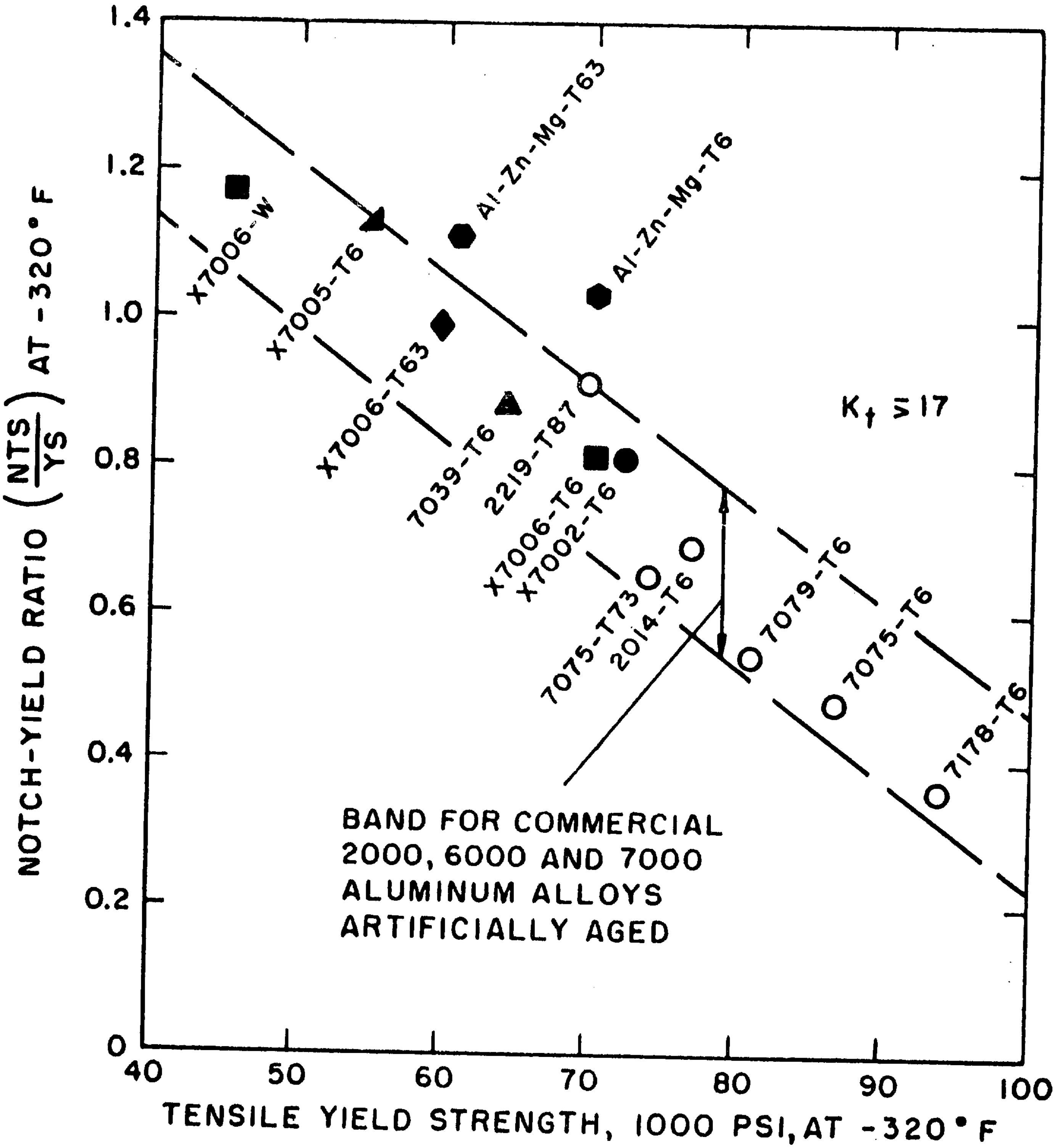

1.2
1.0
0.8
0.6
NOTCH - TENSILE RATIO
1.4
1.2
1.0
0.8
0.6
NOTCH - YIELD RATIO
2219 - T31
2024 - T3
2219 - T37
2219 - T81
2219 - T87
2014 - T6
2024 - T86
2020 - T6
7079 - T6
7075 - T6
7178 - T6
30
40
50
60
70
80
90x10³
TENSILE YIELD STRENGTH - psi

FIGURE 9



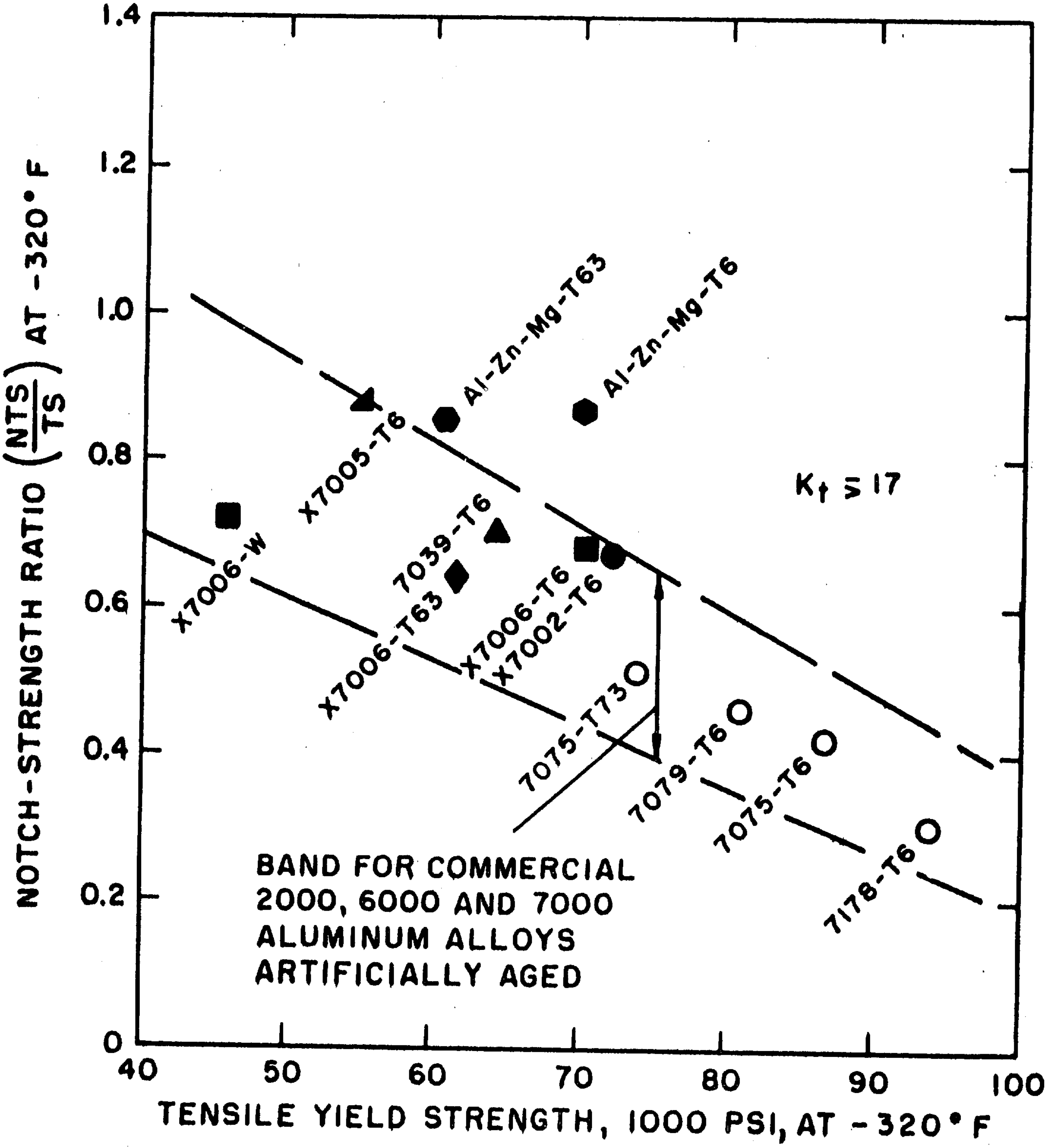
TEAR STRENGTH-YIELD RATIO
0
0.4
0.8
1.2
1.6
2.0
2.4
TENSILE YIELD STRENGTH - psi
30
40
50
60
70
80
90x10³
NOTCH ROOT RADIUS ≦ 0.001"
2 1/4"
1"
1 7/16"
2020-T4
2219-T4
2014-T3*
2024-T4
2219-T81
2219-T37
2219-T87
2024-T36*
2024-T81*
2014-T6
2024-T86*
2024-T86
2020-T6
* ALCLAD
X7277-T6
7079-T6
7075-T6
7178-T6

FIGURE 10



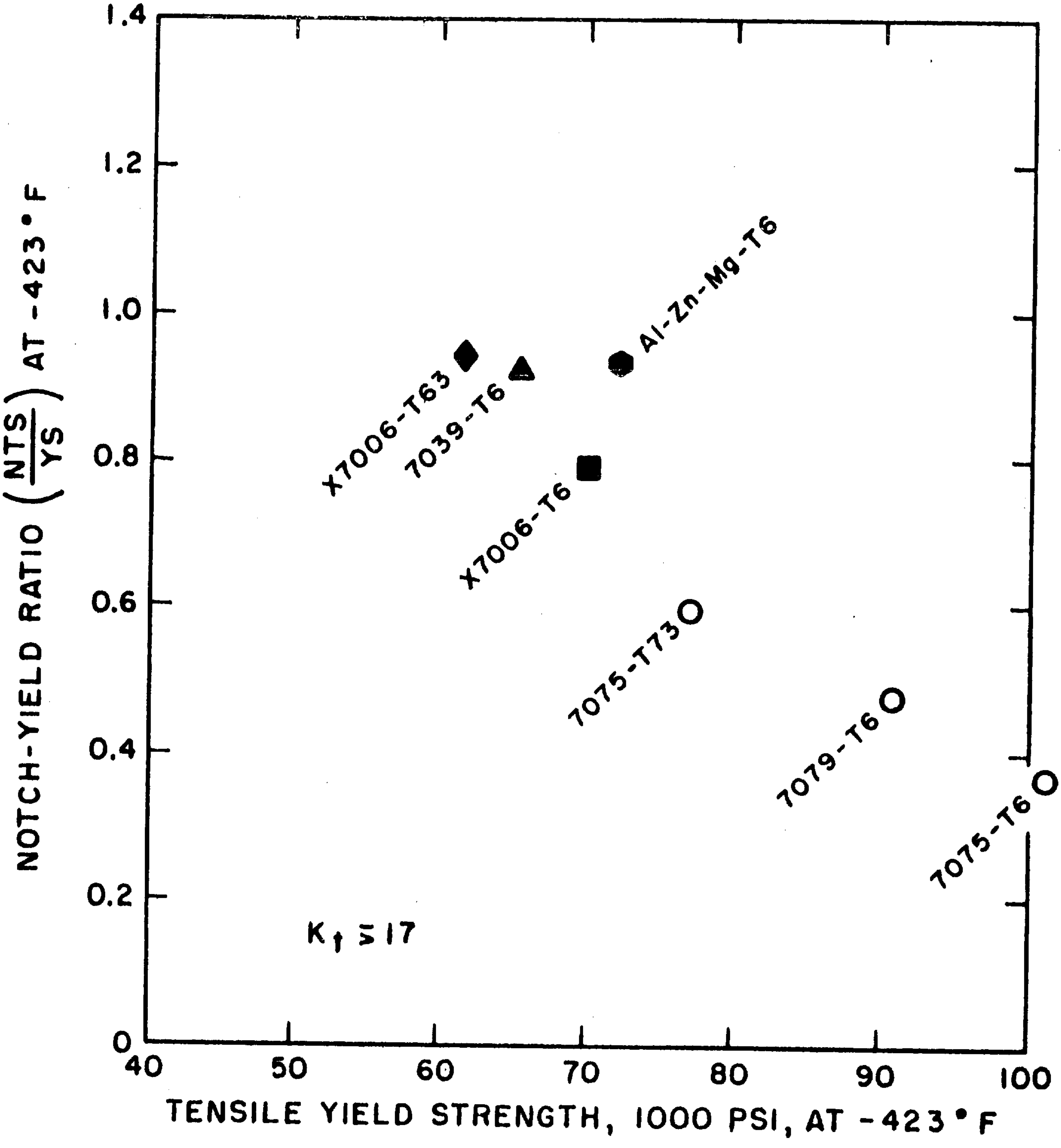
RELATIONSHIP BETWEEN NOTCH-YIELD RATIO AND TENSILE YIELD STRENGTH AT -320° F 0.063 IN. THICK SHEET; TRANSVERSE

FIGURE 11



RELATIONSHIP BETWEEN NOTCH-STRENGTH RATIO AND TENSILE YIELD STRENGTH AT -320° F 0.063 IN. THICK SHEET; TRANSVERSE

FIGURE 12



RELATIONSHIP BETWEEN NOTCH-YIELD RATIO AND TENSILE YIELD STRENGTH AT -423° F
0.063 IN. THICK SHEET; TRANSVERSE

FIGURE 13

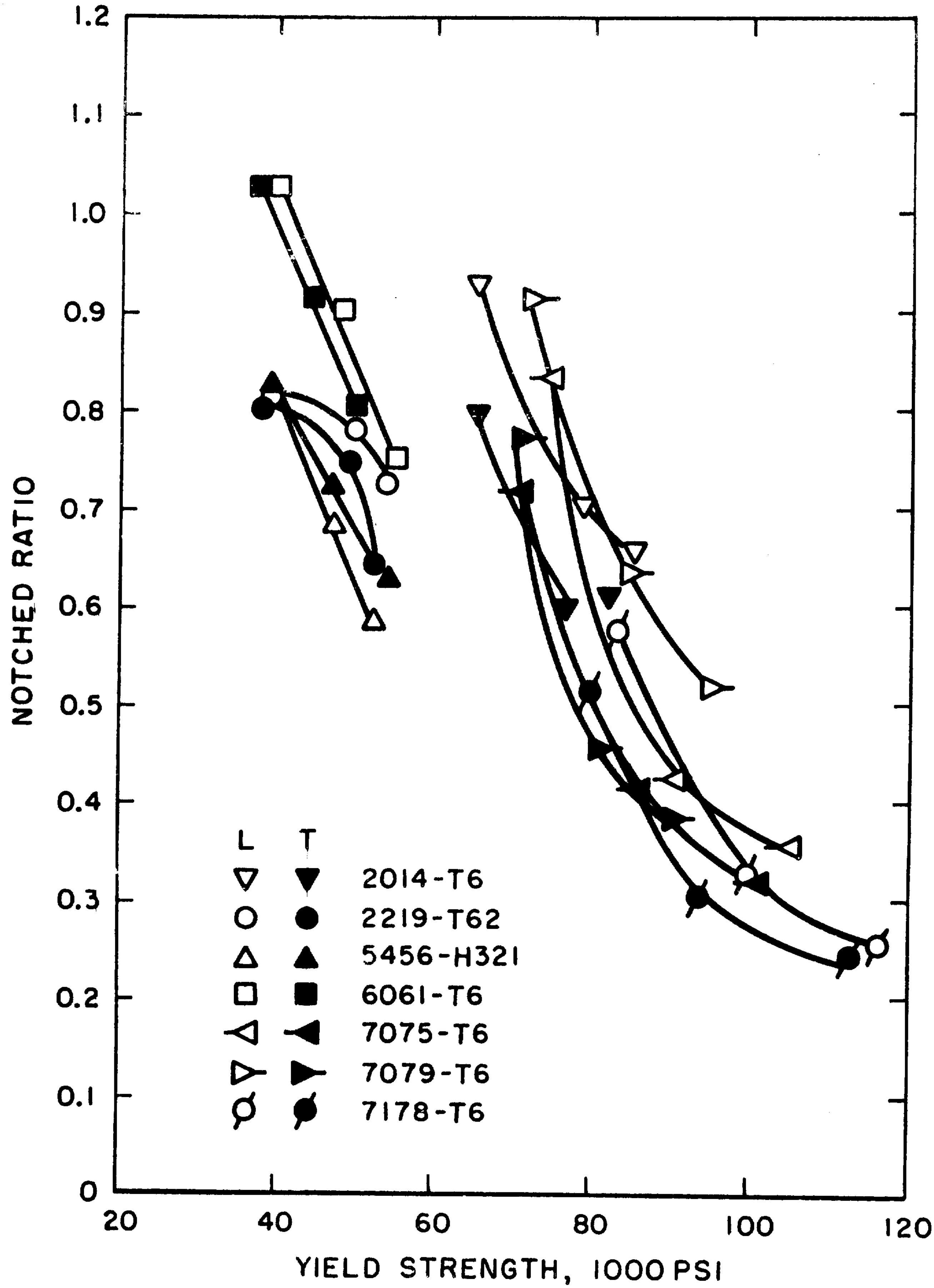


FIGURE 14 – NOTCHED RATIO VERSUS YIELD STRENGTH OF LISTED UNWELDED ALLOYS

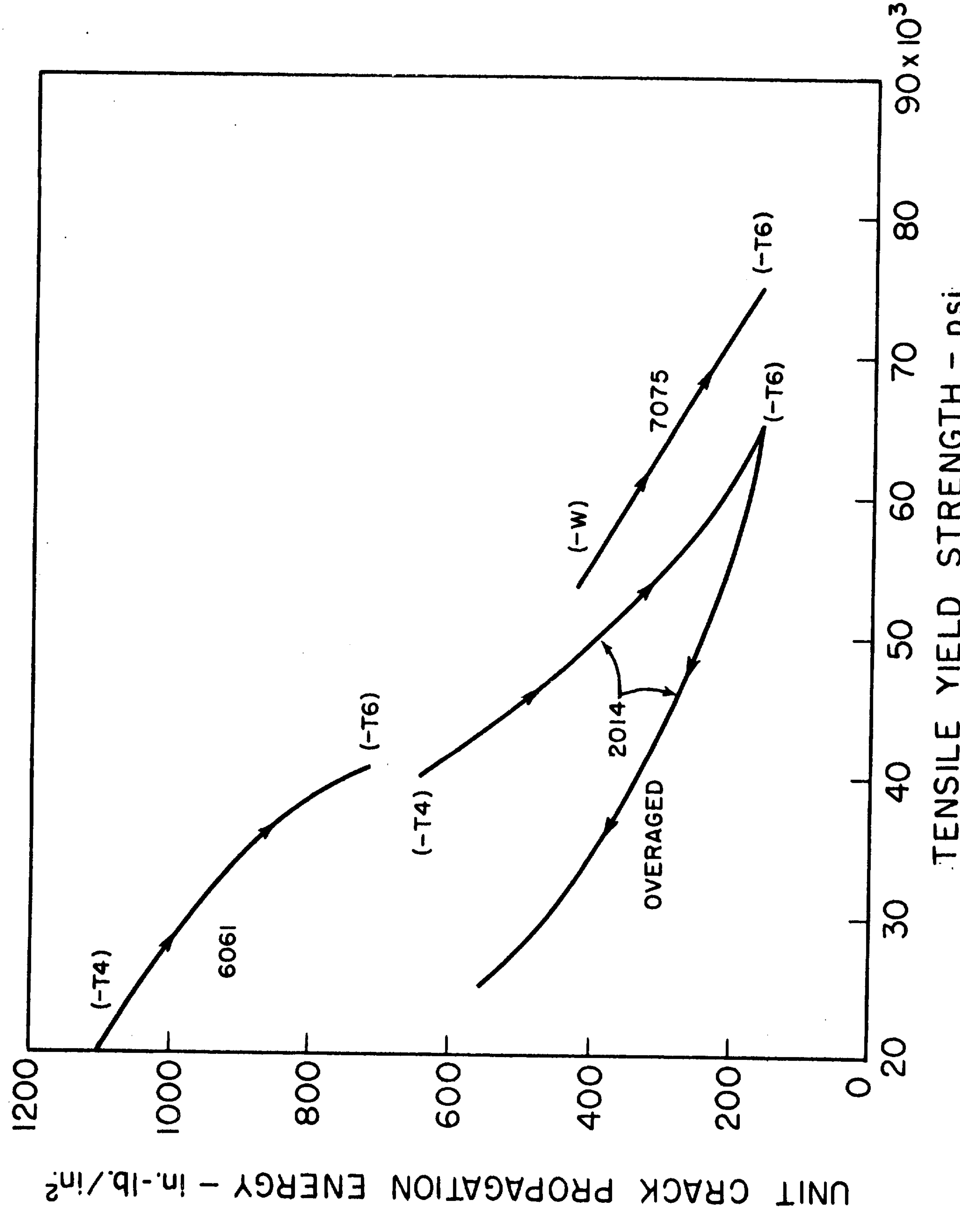

UNIT CRACK PROPAGATION ENERGY - in.-lb./in.²
TENSILE YIELD STRENGTH - psi
0
200
400
600
800
1000
1200
20
30
40
50
60
70
80
90x10³
6061
(-T4)
(-T6)
2014
(-T4)
(-T6)
OVERAGED
7075
(-W)
(-T6)

FIGURE 15

BIBLIOGRAPHY

BIBLIOGRAPHY

1963

63- 1 Anderson, W.A., Kaufman, J.G., and Kane, J.E.; "Notch Sensitivity of Some New Al-Zn-Mg Alloys at Cryogenic Temperatures." Paper presented at 1963 Cryogenic Engineering Conference, August 19, 1963.

63- 2 Betz, I.G., Hussey, F.W., Marcus, H., and Schillinger, D.E.; "Welding Aluminum Alloys;" ORDNANCE, 48, 70-72 (July-August 1963).

63- 3 Baysinger, F.R.; Kaiser Aluminum & Chemical Corp.; "Investigation of Welding and Fabricability of Kaiser Experimental Alloy MR39A;" (January 10, 1963), Interim Project Report No. MS PR 63-1.

63- 4 Christian, J.L. and Hurlick, A.; "Physical and Mechanical Properties of Pressure Vessel Materials for Application of a Cryogenic Environment;" Part II, (April 1963), WASD-TR 62-258-Pt II.

63- 5 D'Annessa, A.T. and Schapiro, L.; "Evaluation of Fusion Welded X7000 Series Aluminum Alloys;" Monthly Progress Report No. 2, Orgn. 52-30, Lockheed Missiles and Space Co. (April 1, 1963).

63- 6 Groth, W.; "What the Space Program Can Tell Us About Trends in Welding Aluminum;" METAL PROGRESS, 83, 76-77, 112-20 (June 1963).

63- 7 Gruhl, W.; "Study of the Problem of the Stress Corrosion Behavior of Al-Zn-Mg 3;" Z. METALLKUNDE, 54, 86-91 (1963).

63- 8 Hug, H.; "Unidur;" ALUMINIUM SUISSE, 13, 49-65 (March 1963).

63- 9 Kaufman, J.G., Nelson, F.G., and Johnson, E.W.; "The Properties of Aluminum Alloy 2219 Sheet, Plate, and Welded Joints at Low Temperatures;" ADV. CRYOGENIC ENG., 8, 661-70 (1963).

63-10 Kaufman, J.G. and Johnson, E.W.; "Notch Sensitivity of Aluminum Alloy Sheet and Plate at -320°F Based Upon Notch-Yield Ratio;" ADV. CRYOGENIC ENG., 8, 678-85 (1963).

63-11 Kaufman, J.G. and Johnson, E.W.; "The Use of Notch-Yield Ratio to Evaluate the Notch Sensitivity of Aluminum Alloy Sheet;" ASTM PROCEEDINGS, 62, 778-91 (1962).

63-12 Nock, J.A., Jr., and Hunsicker, H.Y.; "High Strength Aluminum Alloys;" J. OF METALS, 15, 216-24 (March 1963).

63-13 Nuernberger, H.H.; "Alcoa Aluminum Alloy X7006;" ALCOA BOOKLET (July 1963).

63-14 Schillinger, D.E., Betz, I.G., Hussey, F.W., and Markus, H.; "Improved Weld Strength in 2000 Series Aluminum Alloys;" WELDING JOURNAL, 42, 269s-75s (June 1963).

63-15 Terrill, J.R.; "Improvement of Mechanical Properties in Welded, High Strength, Heat Treatable Aluminum Alloys;" Alcoa Progress Report, June 1963, Contract DA-36-034-ORD-3237A.

63-16 Kaufman, J.G.; "Notch Sensitivity of 1/8" Thick Aluminum Alloy Sheet and Welded Joints at Room Temperature and Subzero Temperatures;" ARL Report No. 9-63-14 (March 29, 1963).

63-17 Westerlund, R.W.; "Progress Report No. 1 - Phase IIa, Experimental Program. Contract No. NAS 8-5452 (August 15, 1963).

63-18 DeMoney, F.W.; "Performance of a New Cryogenic Aluminum Alloy, 7039;" Paper presented at the 1963 Cryogenic Engineering Conference, August 19, 1963.

1962

62- 1 Adams, D.F. and Dinsdale, W.O.; "Effects of Chilling During Welding on the Static and Fatigue Properties of HS30 Aluminum Alloy;" BRIT. WELDING JOURNAL, 9, 559-66 (1962).

62- 2 Bergstedt, P.; General Dynamics/Astronautics; "Compilation of Materials Research Data;" (March 1962), AD-273065.

62- 3 Booth, F.F. and Budd, M.K.; "Corrosion Behaviour of TIG Welds in Aluminum Shipbuilding Alloys;" WELDING AND MET. FAB., 30, 483-86 (December 1962).

62- 4 Campbell, J.E.; "Compilation of Tensile Properties of High-Strength Alloys;" (April 23, 1962); AD 275263, DMIC Memo 150.

62- 5 Cataldo, C.E.; "Weldability Studies of 5456-H343 and 2219-T87 Aluminum Alloy Plates;" Marshall Space Flight Center, Internal Note IN-P & VE-M-62-2 (April 2, 1962).

62- 6 Christian, J.L.; "Mechanical Properties of High-strength Sheet Materials at Cryogenic Temperatures;" General Dynamics, Sponsored Res. Program No. 111-9411, ERR-AN-255 (November 28, 1962).

62- 7 Christian, J.L.; General Dynamics/Astronautics; "Physical and Mechanical Properties of Pressure Vessel Material for Application in a Cryogenic Environment;" (August 31, 1962), AD-291570.

62- 8 Christian, J.L. and Watson, J.F.; General Dynamics/Astronautics; "Mechanical Properties of Several 2000 and 6000 series Aluminum Alloys at Cryogenic Temperatures;" (December 1, 1962), AD-291523.

62- 9 Collins, F.R.; "Improved Strengths in Welded High-Strength Heat-Treatable Aluminum Alloys;" WELDING JOURNAL, 41, 337s-450s (August 1962).

62-10 Durham, R.J.; "Notch Strength of Some Aluminum Alloys at Low Temperatures;" MATERIALS RES., 1, 33-36 (April 1962).

62-11 Fluornoy, F.W.; "Aluminum Alloys for Cryogenic Equipment;" LIGHT METAL AGE, 19(3), 10-12, 28 (1962).

62-12 Gadeau, R.; "Aluminum Alloys in Cryogenics;" REV. ALUMINIUM, 39, No. 304, 1355-69 (December 1962).

62-13 Ghena, P.F.; General Dynamics; "Material, 7079-T652 Aluminum Alloy Tensile and Fatigue Properties, Determination of;" (January 16, 1962), AD-272105.

62-14 Glassman, L.H. and McEvely, A.J., Jr.; "Effects of Constituent Particles on the Notch-Sensitivity Fatigue-Crack-Propagation Characteristics of Al-Zn-Mg Alloys;" (April 1962), NASA TN D928, AD 279565.

62-15 Gruhl, W.; "The Temperature Dependence of the Stress Corrosion Cracking of Al-Zn-Mg 3;" Z. METALLKUNDE, 53, 670-75 (1962).

62-16 Hickey, C.F.; Watertown Arsenal Labs.; "Mechanical Properties of Titanium and Aluminum Alloys at Cryogenic Temperatures;" (March 1962), AD-275483.

62-17 Hickey, C.F.; "Mechanical Properties of Titanium and Aluminum Alloys at Cryogenic Temperatures;" PROC. ASTM, 62, 765-76 (1962).

62-18 Kaiser Aluminum and Chemical Corp.; "Alloy 7039 for Cryogenics;" KAISER BOOKLET (November 1962).

62-19 Kaufman, J.G. and Nelson, F.G.; "Cryogenic Temperatures Up Fatigue Strengths of Al-Mg Alloys;" SPACE/AERONAUTICS, 38, 91-93, 96 (July 1962).

62-20 Nuernberger, H.H.; "Alcoa Aluminum Alloys 6070 and 6071;" Alcoa Green Letter (June 15, 1962).

62-21 Lismer, R.E.; "Properties of Some Alloys and Weld Metal Deposits at Low Temperatures;" WELDING AND MET. FAB., 30, 19-26, 75-85 (1962).

62-22 Livanov, V.A., Yelagin, V.I., Ekhina, Ye.V.; "Stress Corrosion and Mechanical Properties of High-Mg Al-Base Alloys;" AKAD. NAUK SSSR INSTITUT. METALLURGII. ISSLEDOVANIYE SPLAVOV TSVETNYKH METALLOV., 3, 169-79 (1962).

62-23 McDonnell Aircraft Corp.; "Low and Room Temperature Tensile Properties of 2219-T87 Aluminum Alloy;" (October 10, 1962), AD-285888.

62-24 McDonnell Aircraft Corp.; "MIG Welding of Al-Mg Alloy 5456;" (October 10, 1962), AD-285887.

62-25 Mayer, L.W.; "Alcoa Aluminum Alloy 2219;" ALCOA BOOKLET (December 1962).

62-26 Mori, L.; "Mechanical and Elastic Properties of the Principal Light Alloys for Plastic Working Between -200° and +475°C;" Reports of the Instituto Sperimentale dei Metalli Leggeri, Series XII, No. 292 (1962).

62-27 Pumphrey, W.I.; "Developments in Arc Welding;" METALLURGIA, 65, 159-63 (1962).

62-28 Republic Aviation Corp.; "Compilation of Unpublished Materials Information;" (March 31, 1962), AD-274289.

62-29 Rice, L.P., Campbell, J.E., and Simmons, W.F.; "The Tensile Property Evaluation of One 5000-Series Aluminum Alloy at the Temperature of Liquid Helium;" ADV. CRYOGENIC ENG., 8, 671-77 (1962).

62-30 Rice, L.P. and Others; Battelle Memorial Institute; "Tensile-Property Evaluation of the 5000-Series Aluminum Alloy at the Temperature of Liquid Helium;" Report (July 31, 1962).

62-31 Robinson, I.B., Collins, F.R., and Dowd, J.D.; "Welding High-Strength Aluminum Alloys;" WELDING JOURNAL, 41, 221s-28s (1962).

62-32 Sprowls, D.O. and Brown, R.H.; "Resistance of Wrought High-Strength Aluminum Alloys to Stress Corrosion;" ALCOA RESEARCH LABORATORIES TECHNICAL PAPER NO. 17, 32 (Aluminum Company of America) (1962); also published "What Every Good Engineer Should Know About Stress Corrosion of Aluminum;" METAL PROGRESS, 81, 79-85 (April 1962).

62-33 Spuhler, E.H. and Burton, C.L.; "Avoiding Stress Corrosion Cracking in High Strength Aluminum Structures;" ALCOA BOOKLET (1962).

62-34 Thomas, F.W.; Lockheed Nuclear Products; "Effect of Nuclear Radiation on Materials at Cryogenic Temperature. Pedigrees of Metals and Alloys;" (February 1962), NASA N62 15709.

62-35 Woldman, N.E.; ENGINEERING ALLOYS: Fourth Edition; Reinhold Publishing Corp., New York (1962).

62-36 Yusuff, S.; "Fracture Phenomena in Metal Plates;" AIRCRAFT ENGR., 34, 140-48 (May 1962).

62-37 Zakharov, M.V., Mal'tsev, M.V., Vorin, F.A., Rogelberg, L.N., Volkov, Yu.A., Solomasoo, S.D., Fiveyskaya, V.I., and Sokolova, T.I.; "High-Strength Deformable Aluminum-Base Alloy;" BYULLETEN IZOBRETENIY, 4, 44 (1962).

1961

61- 1 Achbach, W.P. and Favor, R.J.; Battelle Memorial Institute; "Design Properties as Affected by Cryogenic Temperatures (Ti-6Al-4V, AISI 4340, and 7079-T6 Alloys);" (January 24, 1961), DMIC Memo 81, AD-250169.

61- 2 Bailey, J.C. and Eldridge, G.W.; "Factors Influencing the Properties of Welds in Aluminium;" BRITISH WELDING JOURNAL, 8, 227-236 (May 1961).

61- 3 Banks, S.R. and Smith, R.E.; "Some Design Considerations for Welded Aluminium;" BRITISH WELDING JOURNAL, 8, 199-206 (May 1961).

61- 4 Beresnev, A.S.; "Causes of Blisters and Cracks in AMg6 Alloy Seam Welded Vessels;" SVAROCHNOE PROIZVODSTVO, 2, 33-34 (February 1961).

61- 5 Brenner, P.; "Heat Treatable Aluminum Alloys as Materials for Welded Structures;" VDI ZEITSCRIFT, 103, 781-90 (1961).

61- 6 Brodskii, A.Ya., et.al.; "Weldability of the B92T Al Alloy;" SAVAROCHNOE PROIZVODSTVO, 7, 13-17 (1961); C.A., 55, 26978 (1961).

61- 7 Buray, Z.; "Reduction of the Cracking Tendency of Some Al Alloys With Certain Additional Elements;" ACTA. TECH., AKAD. SCI. HUNG., 32, 93-118 (1961).

61- 8 Buryak, I.V.; "48-AE-1 Electrodes for Manual Welding of Aluminum-Magnesium Alloys;" SVARKA-SBORNIK STATEY, Leningrad (1958), p. 175-86. Transl. Office Tech. Svs. (Draft) MCL-496/1 (March 1961).

61- 9 Campbell, J.E.; "Review of Current Data on the Tensile Properties of Metals at Low Temperatures;" (February 14, 1961), AD 252484, DMIC Rpt. 148.

61-10 Christian, J.L. and Watson, J.F.; "Mechanical Properties of Several 5000-Series Aluminum Alloys at Cryogenic Temperatures;" ADV. CRYOGENIC ENG., 7, 490-99 (1961).

61-11 Collins, F.R.; Aluminum Company of America; "Investigation Toward Obtaining Significantly Higher Mechanical Properties of As-Welded Joints in High-Strength, Heat Treatable Aluminum Alloys;" Report No. 2-61-44, (September 6, 1961), AD-268649.

61-12 Cooke, V.W. and Powell, R.C.; "Materials for Space Pressure Vessels;" JOURNAL OF METALS, 13, 198-200 (1961).

61-13 Crane, C.H. and Smith, W.G.; "Application of 2219 Al Alloy to Missile Pressure-Vessel Fabrication;" WELDING JOURNAL, 40, 33s-40s (1961).

61-14 Demoney, F.W. and Wolfer, G.C.; "Tensile and Impact Properties of 7075-T6 and 7079-T6 Plate, Hand Forgings, and Tensile Properties of Plate MIG Weldments Between 75°F and -320°F;" ADV. CRYOGENIC ENGIN., 7, 466-76 (1961).

61-15 Derry, L.W. and Layton, A.W.J.; Ministry of Aviation (Gt. Brit.); "The Strength Properties of Aluminum Alloys DTD 5010 and DTD 5020 in the Form of 1-In. and 3-In. Plates. Part 3: Properties of 3-In. Plate to Spec. DTD 5010;" (December 1961), AD-271697.

61-16 Durham, R.J.; "Mechanical Properties of Aluminum Alloys for the Transport of Liquified Gases at Low Temperatures;" ALUMINIUM, 37, 792-801 (December 1961).

61-17 Durham, T.F. and Others; National Bureau of Standards; "Cryogenic Materials Data Handbook;" (1961).

61-18 Eldridge, E.A. and Deem, H.W.; "Report on the Physical Properties of Met. and Alloys from Cryogenic to Elevated Temperatures;" ASTM Special Technical Publication 296 (1961).

61-19 Hess, J.B., Person, N.L., and Krill, F.M.; Kaiser Aluminum and Chemical Corp.; "Correlation of Ballistic Penetration Resistance and Spalling Tendency with Mechanical Properties and Microstructure in 5083, MR19, and MR20 Aluminum Alloy Armor Plate Samples;" (March 1, 1961), AD-252042.

61-20 Hess, J.B.; Kaiser Aluminum and Chemical Corp.; "Study in Welding High Strength Aluminum Alloys, and Study of Effect of Alloy Compositions and Temper as Well as Ingot Quality and Plate Quality on the Weldability, Mechanical and Ballistic Properties of Medium and High Strength Aluminum Base Armor;" (October 17, 1961), AD-265145.

61-21 Houldcroft, P.T.; "Investigation of Filler Materials for Welding Al-Zn-Mg Alloys;" BRITISH WELDING JOURNAL, 8, 360-65 (July 1961).

61-22 Hurlich, A. and Watson, J.F.; "Selection of Metals for Use at Cryogenic Temperatures;" METAL PROGRESS, 79, 65-72 (April 1961).

61-23 Ida, N.N., Rupert, and Others; Martin Marietta Corp.; "High-Strength Aluminum Alloy Program;" (August 1961), AD-274880.

61-24 Izdinsky, O.; "Mechanical Properties of Welds of Aluminum Alloy 424201.6;" ZVARAC, SYMPOS., 10, No. 3, 296-308 (1961); ABSTR. J. MET., 48, 478 (1962).

61-25 Kaufman, J.G. and Johnson, E.W.; "New Data on Aluminum Alloys for Cryogenic Applications;" ADV. CRYOGENIC ENGIN., 6, 637-49 (1961).

61-26 Kelsey, R.A.; Aluminum Company of America; "Strength of Welded Panels of 2014 and 2219 Sheet as Determined by Tension and Bulge Tests;" Report No. 12-61-37 (June 6, 1961), AD-269798.

61-27 King, E.J.; Bell Aerosystems Co.; "Investigation of Aluminum Alloy 6061-T4-T6 Welded and Unwelded;" (December 29, 1961), AD-276982.

61-28 Liptak, J.A.; "Gas Metal-Arc Welding Al with Large Diameter Fillets;" WELDING JOURNAL, 40, 917-27 (1961).

61-29 Markovich, R.; "Biaxial Mechanical Properties of High-Strength Weldable Alloys;" ADV. CRYOGENIC ENGIN., 7, 459-65 (1961).

61-30 Nielsen, H.; "The Mechanical Properties of Wrought Al-Mg Alloys at Low Temperatures;" ALUMINIUM, 37, 802-07 (1961).

61-31 Nock, J.A., Jr., Holt, M., and Sprowls, D.O.; "A New High-strength Aluminum Alloy;" METAL PROGRESS, 80, No. 3, 87-91 (September 1961).

61-32 Petrov, G.L. and Makarov, A.G.; "The Sensitivity of Al-Zn-Mg Alloys to Hot Cracking During Welding;" AVTOMAT. SVARKA., 83, 24-32 (September 1961); LIGHT METALS BULL., 24, 839 (August 15, 1962).

61-33 Rice, L.F., Campbell, J.E., and Simmons, W.F.; "Cryogenics. Tensile Behavior of the 5000 Series Al Alloys at Room and Cryogenic Temperatures;" LIGHT METAL AGE., 19, 9-10 (October 1961).

61-34 Rice, L.P., Campbell, J.E., and Simmons, W.F.; "Tensile Behavior of Parent Metal and Welded 5000-Series Aluminum Alloy Plate at Room and Cryogenic Temperatures;" ADV. CRYOGENIC ENGIN., 7, 478-89 (1961).

61-35 Sears, S.L. and Crial, R.S.; "Welding 2219 Al for Bomarc Fuel Tanks;" METAL PROGRESS, 80, 88-99 (November 1961).

61-36 Schwartzberg, F.R. and Keys, R.D.; Martin-Marietta Corp.; "Mechanical Properties of 2000 Series Aluminum Alloys at Cryogenic Temperatures;" (October 1961), AD-285965.

61-37 Ward, O.T.; Convair Astronautics; "Mechanical Properties of 6061-T6 Al Alloy. TIG and MIG, Welds;" (August 16, 1961), AD-273909.

61-38 WELDING HANDBOOK; Fourth Edition; Section IV; American Welding Society, N.Y. (1961).

61-39 Zenner, G.H.; "What Metal Should I Use for Fabrication of Cryogenic Vessels and Equipment?" METAL PROGRESS, 80, 110-15, 54, 56 (October 1961).

61-40 Miller, P.C.; Marshall Space Flight Center; "Low Temperature Mechanical Properties of Several Al Alloys and Their Weldments;" (October 2, 1961), MTP - S&M-M-61-16.

1960

60- 1 Aluminum Dev. Association; "Arc Welding of Al;" AL DEV. ASSN. INFORMATION BULL., No. 19 (1960).

60- 2 Daley, D.M., Jr.; "Techniques for Welding Al-Mg Alloys;" WELDING JOURNAL, 39, 301s-305s (July 1960).

60- 3 DeMoney, F.W. and Wolfer, G.C.; "The Fatigue Properties of Aluminum Alloy 5083-H113 Plate and Butt Weldments at 75° and -300°F;" ADV. CRYOGENIC ENGIN., 6, 590-603 (1960).

60- 4 Eldrige, G.W.; "Recent Advances in Joining Aluminium;" METALLURGIA, 61, 55-60 (1960).

60- 5 Everest, A.; "The Behavior of High Magnesium Content Aluminum Alloys at Room and Liquid Nitrogen Temperatures;" ADV. CRYOGENIC ENGIN., 5, 385-96 (1960).

60- 6 Hanson, M.P., Stickley, G.W., and Richards, H.T.; "Sharp-Notch Behavior of Some High-Strength Sheet Aluminum Alloys and Welded Joints at 75°, -320°, and -423°F;" ASTM Special Technical Publication 287, 3-15 (1960). Also discussion by Brown, J.A., Freymeyer, R.D., and Rawe, R.A.

60- 7 Kasen, M.B. and Pfluger, A.R.; Kaiser Aluminum and Chemical Corp.; "The Development of Improved Filler Alloys for Inert-Gas Tungsten-Arc Welding High Strength Aluminum Alloys;" (May 12, 1960); AD-236 396.

60- 8 Kaufman, J.G.; Aluminum Company of America; "Mechanical Properties of Plain and Welded 6061 Aluminum Alloy at Subzero Temperatures;" (July 7, 1960); AD-249963, Report No. 9-60-26.

60- 9 Kaufman, J.G. and Johnson, E.W.; "New Data on Aluminum Alloys for Cryogenic Applications;" ADV. CRYOGENIC ENGIN., 6, 637-49 (1960).

60-10 Kuschell, K.E.; Northrop Corp.; "Room and Elevated Temperature Properties of Aluminum Forging Alloy 2618-T61;" (April 6, 1960); AD-270416.

60-11 Lashko-Avakyan, S.V., and Lashko, N.F.; "Intercrystalline Crystallization Cracks in Casting and Welding Aluminum Alloys, Hot Cracks in the Welded Joints of Billets and Casting;" Translated from Russian; Office Tech. Info. ASTIA 257 153 (October 1960).

60-12 Lashko-Avakyan, S.V., and Lashko, N.F.; "Shrinkage Phenomena and the Problem of Weldability of Aluminum Alloys;" USADOCH. PROTSESSY V. METALLAKH. MOSCOW AKAD. NAUK. SSSR, 198-205 (1960). ABSTR. J. MET., B2, 71 (1961).

60-13 Lucas, W.R., and Cataldo, C.E.; "Some Low-Temperature Properties of Al Alloy Weldments;" ASTM Special Technical Publication 287, 23-36 (1960).

60-14 Mudrack, K.P.; "Investigation of the Welding of Alloy Al-Zn-Mg 1 With Special Reference to Sensitivity to Weld Cr;" SCHWEISSEN U SCHNEEDEN, 12, 45-55 (1960). MET. ABSTR., 28, 77 (September 1960).

60-15 National Bureau of Standards; "Cryogenic Materials Data Handbook;" NBS CRYOGENIC ENG. LAB., (January 1960); Contract AF04(647)-59-3; PB161093.

60-16 Nuccitelli, S.A., and Mote, M.W., Jr.; "Mechanical Testing of Al Weldments;" ADV. CRYOGENIC ENGIN., 4, 114-22 (1960).

60-17 Ochieano, M.L.; "Development of Flashwelding Techniques for Non-Ferrous Alloys;" Lockheed; AMC Tech. Rpt. 60-7-250a (March 1960).

60-18 Olleman, R.D., and Wolfer, G.C.; "The Tensile and Impact Properties of Plate and Welds of Al Alloys 5083-H113 Between 75 and -320°F;" ADV. CRYOGENIC ENGIN., 5, 430 (1960).

60-19 Orysh, M.S., and Betz, I.G.; "Weldability of Al Casting Alloys with 5086 Wrought Al Alloys;" WELDING JOURNAL, 39, 342s-51s (1960).

60-20 Pfuger, A.R. and Kasen, M.B.; Kaiser Aluminum and Chemical; "Welding of Ballistic H Plates from 1-1/4 in. Thick 5083 and 5086 Alloys;" (September 12, 1960), AD-242680.

60-21 Silcock, J.M.; "The Structural Aging Characteristics of Al-Cu-Li Alloys;" J. INST. METALS, 88, 357-64 (1960).

60-22 Spuhler, E.H., Knoll, A.H., and Kaufman, J.G.; "Lithium in Aluminum - X2020;" METAL PROGRESS, 77, 80-83 (June 1960).

60-23 Stern, I.L., Cordiano, H.V., Digiglio, V.A.; "Comparative Properties of Al Alloy Weldments;" WELDING JOURNAL, 39, 424s-32s (1960).

60-24 Tomlinson, J.E. and Wood, J.L.; "Factors Influencing the Fatigue Behavior of Welded Al;" BRITISH WELDING J., 7, 250-64 (1960).

60-25 Watson, J.F.; Convair Astronautics; "Selection of Materials for Cryogenic Applications in Missiles and Aerospace Vehicles;" (February 25, 1960), AD276148.

60-26 White, S.S., Manchester, R.E., Moffatt, W., and Adams, C.E.; "Plastic Properties of Al-Mg Weldments;" WELDING JOURNAL, 39, 10s-19s (January 1960).

1959

59- 1 Abov, A.A. and Bobrov, G.V.; "Modification of the Weld Metal in the Welding of Al;" SVAROCHNOE PROIZVODSTVO, 32, 1-6 (1959): MET. ABSTR., 27, 410 (1960); LIGHT MET. BULL., 22, 409 (1960).

59- 2 Al'tman, M.B., Lotareva, O.B., Laktionova, L.I., and Spiridonova, S.V.; "A Foundry Aluminum Alloy Composed of Al-Mg-Zn-Be-Ti;" BYULLETEN IZOBRETENIY, 7, 42 (1959).

59- 3 Alov, A.A., and Nikitin, V.M.; "Some Metallurgical Problems in the Welding of Al-4 and Al-5 Alloys;" SVAROCHNOE PROIZVODSTO, 28-30 (1958); MET.ABSTR. 26, 501 (February 1959).

59- 4 Anderson, W.A.; "Precipitation Hardening Aluminum-Base Alloys;" PRECIPITATION FROM SOLID SOLUTION, Am. Soc. for Metals, 150-207 (1959).

59-5 Anon.; "High Strength Welds in Aluminum;" PRECISION METAL MOLDING, 17, 52-53 (August 1959).

59- 6 Arnold, S.V.; Watertown Arsenal Laboratories; "Notch Sensitivity and Laminated Charpy Impact Strength of 1100-F and 2024-T4 Aluminum Alloy Simulated Sheet;" (September 1959), WAL TR 341.5/1, AD-225559.

59- 7 Buray, Z.; "Examination of Alloys of Type Al-Mg-Zn of Average Strength for Strength and Resistance to Cracks in Welding;" FEMIPARI KUTATO INT. KOZL., 3, 157-71, 439, 449, 459 (1959); ABSTR. J. MET., B 11, 69 (1960).

59- 8 Daley, Daniel; Army Ballistic Missile Agency; "Fusion Welding of X2219-T6 Aluminum Alloy;" (May 7, 1959), DRF-TM-09-59.

59- 9 Deesing, E.F. and Ketcham, S.J.; "Exploratory Investigation of X2020 High Temperature Aluminum Alloy;" (April 9, 1959), NAMC-AML-AE 4195, Pt. II, AD217102.

59-10 Gonchar, V.N.; "Influence of Copper on the Aging of Aluminum Alloys Containing Magnesium and Zinc;" TRUDY LENINGRAD. POLITEKH. INST. IM. M.I.KALININA, No. 202, 44-55 (1959); Fulmer Translation No. 156.

59-11 McGee, R.L., Campbell, J.E., Carlson, R.L., and Manning, G.K.; "How Low Temperatures Affect Nine High-Strength Alloys;" MATLS. IN DESIGN ENGIN., 50, 106-07 (November 1959).

59-12 M.I.T.; "Toughness of Aluminum-Magnesium Weldments;" (February 1959), AD-212419.

59-13 Newman, R.P.; "Fatigue Tests on Butt Welded Joints in Al Alloys HE.30 and NP.5/6;" BRIT. WELDING J., 6, 324-32 (1959); 7, 365-80 (1960).

59-14 Oxborrow, S.D.; General Dynamics; "Material - 7079-T6 Aluminum Alloy Extrusions Room and Elevated Temperature Properties - Determination of;" (August 27, 1959), AD-272161.

59-15 Scott, R.B.; CRYOGENIC ENGINEERING; 368 pp; D. Van Nostrand Co., New York (1959).

59-16 Wilson, W.A.; Army Ballistic Missile Agency; "Development of Welding Technique for 7075 Aluminum Alloy;" (April 10, 1959), DFR-TN-03-59.

1958

58- 1 Dies, K.; "Use of Al-Zn-Mg Alloys as Material for Welded Structures;" VEREINIGTE DEUTSCHE METALLIVERKE AG., German Patent 1,107,945, App'l. March 8, 1958.

58- 2 Dix, E.H., Jr., Anderson, W.A., and Shumaker, M.B.; "Development of Wrought Aluminum-Magnesium Alloys;" ALCOA RESEARCH LABORATORIES TECHNICAL PAPER No. 14 (1958), 66 pp., Aluminum Company of America.

58- 3 Durham, R.J.; "Extruded Aluminium Alloys for Low Temperature Service;" BRIT. WELDING J., 5, 510-16 (November 1958).

58- 4 Hendricks, Paul L.; Wright-Patterson Air Force Base; "Metallurgical Investigation of Aluminum Alloy X2219-T6;" (June 1958), WADC TN 58-57, AD-155672.

58- 5 Houldcroft, P.T.; "Welding of High-Strength Heat-Treated Al Alloys;" BRIT. WELDING J., 5, 261-71 (June 1958).

58- 6 Houldcroft, P.T. and Fidgeon, F.; "Aging Characteristics of 'As-Deposited' Aluminum Alloy Weld Metal;" BRIT. WELDING J., 5, 319-26 (July 1958).

58- 7 Lismer, R.E.; "Low Temperature Properties of Aluminum-Magnesium Alloys;" BRIT. WELDING J., 5, 523-538 (November 1958).

58- 8 Mikesell, R.P. and Reed, R.P.; "The Tensile and Impact Strength of Annealed and Welded 5086 Al Down to 20°FK;" ADV. CRYOGENIC ENGIN., 4, 101-13 (1958).

58- 9 Mori, L.; "Mechanical Properties of the Light Alloys at Low Temperatures;" ALUMINIO, 27, 495-501 (1958).

58-10 Sawkill, J. and James, D.; "Tear Tests on Aluminum-Magnesium Alloy Plate;" BRIT. WELDING J., 5, 517-22 (November 1958).

58-11 Tomlinson, J.E. and Jackson, D.R.; "Low Temperature Properties of Welded and Unwelded Al-5% Mg Alloy Plates;" BRIT. WELDING J., 5, 499-510 (November 1958).

58-12 Varley, P.C., Day, M.K.B., and Sendorek, A.; "The Structure and Mechanical Properties of High-Purity Aluminum-Zinc-Magnesium Alloys;" J. INST. METALS, 86, 337-51 (1958).

1957

57- 1 Baker, J.F. and Tipper, C.E.; "The Value of the Notch Tensile Test;" WELDING RESEARCH COUNCIL BULL., Series No. 37 (June 1957).

57- 2 Brenner, P.; "Weldable Al-Mg Alloys;" PROC. INTL. INST. WELDING, Annual Assembly Essen. (July 1, 1957).

57- 3 Chadwick, R., Muir, N.B., and Grainger, H.B.; "Stress Corrosion of Wrought Ternary and Complex Alloys of the Aluminum-Zinc-Magnesium System;" J. INST. METALS, 85, 161-70 (1957).

57- 4 Erdmann-Jesnitzer, F.; "Influence of the Subzero Temperature and Notches on Static Strength of Welded Aluminum Alloy Sheet;" ALUMINIUM, 33, 376-84 (1957).

57- 5 Kropschot, R.H., McClintock, R.M., and Van Gundy, D.A.; "Mechanical Properties of Some Engineering Materials Between 20°K and 300°K;" PROC. 1956 Cryogenic Engin. Conf., N.B.S., Boulder, Colo., 93-101 (February 1957).

57- 6 Mikesell, R.P. and Reed, R.P.; "The Impact Testing of Various Alloys at Low Temperatures;" ADV. CRYOGENIC ENGIN., 3, 316-24 (1957).

57- 7 Portnor, N.D. and Geinrikhsdorf, N.G.; "Prevention of Occurrence of Cracking During Welding of Al Alloy Amts;" SVAROCHNOE PROIZVODSTVO, 10, 16-18 (1957); C.A., 52, 1907 (1958).

57- 8 Sutherland, J.G., and Walter, J.; "Investigation of Tensile Strengths of Welded Joints in Alcan, 65S-T, Alcan A56S, and Alcan B54S Sheets and Plates;" ALUMINIUM LAB. LTD, Report K-RR-638-57-27 (September 1957).

56- 1 Groth, W.G. and Matuszeski, R.A.; "Welding of High Strength Al Alloys in Heavy Sections;" WELDING JOURNAL, 35, 616s-22s (1956).

56- 2 Hardy, H.K.; "Trace Element Effects in Some Precipitation Hardening Aluminum Alloys;" J. INST. METALS, 84, 429-39 (1956).

56- 3 Mueller-Busse, A.; "Behavior of Welds in Al-Mg-Zn 1;" ALUMINIUM, 32, 336 (June 1956).

56- 4 Wood, John D.; Wright-Patterson Air Force Base; "Mechanical Property, Corrosion and Welding Studies on 6066 Aluminum Alloy;" (June 1956), WADC TR 56-99, PB 121497.

56- 5 Zoeller, H.W. and Wittman, R.E.; Wright-Patterson Air Force Base; "Properties of XA78S Aluminum Alloy Sheet, Plate, and Extrusions;" (February 1956), AD-91224, WADC TR 54-119.

1955

55- 1 Chyle, J.J. and Kutuchief, I.; A. O. Smith Corp.; "Research and Development on the Welding of Al Plate;" (January 31, 1955), PB 111850.

55- 2 Cook, L.A., Channon, S.L., and Hard, A.R.; "Properties of Welds in Al-Mg-Mn Alloys 5083 and 5086;" WELDING JOURNAL, 34, 112-27 (1955).

55- 3 Dahl, O. and Detert, K.; "Hardening of Aluminium-Magnesium Alloys;" Z. METALLKUNDE, 46, 94-99 (1955).

55- 4 Erdmann-Jesnitzer, F.; "Alloying and Weldability of Al;" KOHASY, LAPOK, 10, 576-87 (1955).

55- 5 Hardy, H.K.; "Aluminium-Copper-Cadmium Sheet Alloys;" J. INST. METALS, 83, 337-46 (1955).

55- 6 Pritchard, Helen R.; Frankford Arsenal; "Correlation of Literature on the Effect of Testing Temperature on the Mechanical Properties of Wrought Aluminum Base Alloys;" (May 1955), PB 131346.

55- 7 Pfluger, A.R. and Kasen, M.B.; Kaiser Aluminum and Chemical Corp.; "Improvement in Weld Soundness by the Use of Halogens and Halides in Inert Gas Metal Arc Welding of Al"; (December 30, 1955), AD-107075, PB 144646.

55- 8 Pumphrey, W.I.; "Researches into the Welding of Al and Its Alloys, A Summary of the Work of the ADA Welding Research Team at the University of Brimingham 1944-1950;" Al Dev. Assn. Rpt. No. 27 (July 1955).

1954

54- 1 Harris, I.R. and Varley, P.C.; "Factors Influencing Brittleness in Aluminum-Magnesium-Silicon Alloys;" J. INST. MET., 82, 379-93 (April 1954).

54- 2 Industr. Test. Lab.; "Strengths of Joints in Al Alloys 54S-H34, and 56S-H34 Welded by the Semi-Automatic Inert-Gas Shielded Metal Arc Process;" (1954), NS-021-200.

54- 3 Muller-Busse, A.; "Cracking of Welds in Al-Based Materials;" ALUMINIUM, 30, 240-50 (June 1954).

1953

53- 1 Martin, D., Jacobson, M.I. and Voldrich, C.B.; "Welding of Thick Plates of High Strength Al Alloys;" WELDING JOURNAL, 32, 161s-71s (April 1953).

53- 2 Pumphrey, W.I.; "An Examination of Welding and Tensile Properties of Some Al-Zn-Mg and Some Al-Cu-Si Alloys;" Al Dev. Assn. Research Rpt No. 18 (November 1953).

1952

52- 1 Dowd, J.D.; "Weld Cracking of Aluminum Alloys;" WELDING JOURNAL, 31, 448s-56s (1952).

52- 2 Fontana, M.G., Bishop, S.M., and Spretnak, J.W.; "Investigation of Mechanical Properties and Physical Metallurgy of Aircraft Alloys at Very Low Temperatures;" (December 1952), WADC TR 5662-V.

52- 3 Hardy, H.K.; "The Aging Characteristics of Ternary Aluminum-Copper Alloys with Cadmium, Indium, or Tin;" J. INST. METALS, 80, 483-92 (1952).

52- 4 Lissher, O.; "Effect of Stretching and Temperature on Stress Corrosion Cracking;" Z. METALLKDE, 43, 147-50 (1952).

52- 5 Matting, A., and Muller-Busse, A.; "Notch Impact Toughness of Light Metal Welds;" METALL., 6, 586-89 (1952).

52- 6 Nelson, F.G., Jr. and Howell, F.M.; "Strength and Ductility in Al Alloy Plate," WELDING JOURNAL, 31, 397s-402s (September 1952).

1951

51- 1 Cook, M., Chalwick, R., and Muir, N.B.; "Observations on Some Wrought Aluminum-Zinc-Magnesium Alloys;" J. INST. METALS, 79, 293-320 (1951).

51- 2 Hardy, H.K.; "The Tensile Properties of Heat Treated Aluminium-Copper and Aluminium-Copper-Cadmium Alloys of Commercial Purity;" J. INST. METALS, 78, 657-66 (1951).

51- 3 Moore, D.C.; "Investigation into the Cracking of the More Common Binary Alloys During Argon Arc Welding;" SHEET MET. IND., 28, 739-52 (1951).

51- 4 Perrymann, E.C.W. and Brook, G.R.; "Mechanism of Precipitation in Aluminum-Magnesium Alloys;" J. INST. METALS, 79, 19-34 (1951).

1950

50- 1 Bogardus, K.O., Stickley, G.W. and Howell, F.M.; "Review of Information on the Mechanical Properties of Al Alloys at Low Temperatures;" (May 1950), NACA TN 2082.

50- 2 Dix, E.H., Jr.; "Aluminum Alloys - 1940 to 1950;" METAL PROGRESS, 58, 484-89 (October 1950).

50- 3 Dix, E.H., Jr.; "Aluminum-Zinc-Magnesium Alloys - Their Development and Commercial Production;" ASM TRANSACTIONS, 42, 1057-1127 (1950).

50- 4 Holland, M.; "Cracking Tendency of Assemblies of Welded Light Alloys;" REV. Al, 27, 175-82 (May 1950).

50- 5 Teed, P.L.; THE PROPERTIES OF METALLIC MATERIALS AT LOW TEMPERATURES; John Wiley & Sons, Inc., N.Y. (1950).

1949

49- 1 Aul, E.L., et.al.; "Tension Properties of Al Alloys in the Presence of Stress Raisers;" (March 1949), NACA TN 1831.

49- 2 Fink, W.L., Keller, F., Sicha, W.E., Nock, J.A., Jr., and Dix, E.H., Jr.; PHYSICAL METALLURGY OF ALUMINUM ALLOYS; 247 pp, Am. Soc. For Metals, Cleveland (1949).

49- 3 Voldrich, M.; "Welded Joints in Thick Al Plates;" WELDING JOURNAL, 28, 275s-88s (June 1949).

1948

48- 1 Biringi, L.K., Williams, R.D., and Voldrich, C.B.; "Investigation on the Welding of High-Strength Al Alloys;" BATTELLE MEMORIAL INST. RPT., 85-134 (March 31, 1948); LIGHT MET. BULL., 11, 1012 (1949).

1947

47- 1 Fink, W.L. and Willey, L.A.; "Quenching of 75S Aluminum Alloy;" METALS TECHNOLOGY, 14, TECHNICAL PUBLICATION 2225 (August 1947); TRANS. AIME, 175, 414-27 (1948).

47- 2 Moore, R.L.; "Static Strength Tests of Fillet Welds on Al Alloy 61S-T Plate;" WELDING JOURNAL, 26, 593s-600s (1947).

47- 3 Herenguel, J.; REV. MET. 44, 77 (1947).

1946

46- 1 Doan, J.P. and McDonald, J.C.; "The Notch Sensitivity in Static and Impact Loading of Some Mg-Base and Al-Base Alloys;" PROC. ASTM, 46, 1097-1118 (1946).

46- 2 Smith, Loren W.; "Corrosion Tests of Multi-Arc Welded High-Strength Al Alloys;" TRANS. ELECTROCHEM. SOC., 89, 83-103 (1946).

1944

44- 1 Petri, H.G., Siebel, G., and Vosskuhler, H.; "The Effect of Additions on the Stress Corrosion Behavior of an Al-Mg-Zn Alloy Containing 4.5% Zn and 3.5% Mg;" ALUMINIUM, 26, 2-10 (1944).

1943

43- 1 Bungardt, W. and Schailberger; "The Stress Corrosion Behavior of Al-Zn-Mg Alloys After Thermal Treatment;" Z. METALLKUNDE, 35, 47-55 (1943).

43- 2 Muhlenbruch, A. and Seeman, H.J.; "Investigations of Wrought Al-Zn-Mg Alloys. III--Tensile Properties and Stress Corrosion in the Hot Age-Hardened Condition;" LUFTFAHRTFORSCH, 19, 337-43 (1943).

1940

40- 1 Hansen, M., Muhlenbruch, A., and Seeman, H.J.; "Stress Corrosion Behavior of Al-Zn-Mg Alloys;" METALLWIRTSCHAFT, 19, 535-37 (1940).

40- 2 Spraragen, W. and Claussen, G.E.; "Welding Aluminum and Its Alloys by Arc, Torch, and Pressure Processes;" Literature Div. Engin. Found.--Welding Research Comm. (April 1940).

1939

39- 1 Brenner, P. and Kostron, H.; "The Aging of Aluminum-Magnesium-Silicon Alloys;" Z. METALLKUNDE, 31, 89-97 (1939).

39- 2 Geller, W.; "Tensile Strength and Elongation of Forging Alloys of the Al-Mg-Si Type;" Z. METALLKUNDE, 31, 9-11 (1939).

39- 3 Meunier, F. and Michel, J.; "Corrosion Resistance of Al-Mg Arc Welded Alloys;" CHIM. ET IND., 41, 209-21 (1939).

1938

38- 1 Vosskuhler, H.; "The Effect of Notches on the Tensile Strength of Al-Mg Alloys with Different Microstructures;" METALWIRTSCH. METALLWIS., 17, 31-34 (1938).

1937

37- 1 Fink, W.L. and Smith, D.W.; "Age-Hardening of Aluminum Alloys, II -- Aluminum-Magnesium Alloys;" METALS TECHNOLOGY, 3, TECHNICAL PUBLICATION, 760 (December 1936); AIME TRANSACTIONS, 124, 162-67 (1937).

1928

28- 1 Brenner, P.; "Lautal As a Structural Material for Aircraft;" LUFTFAHRTFORSCHUNG, 1, 35-94 (1928).